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MODELING ENERGY STORAGE REQUIREMENTS FOR HIGH-ENERGY LASERS ON NAVY SHIPS

by

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June 2018

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**MODELING ENERGY STORAGE REQUIREMENTS FOR HIGH-ENERGY
LASERS ON NAVY SHIPS**

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Submitted in partial fulfillment of the
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ABSTRACT

The Navy requires a weapon system that effectively counters swarms of unmanned aerial vehicles (UAVs), anti-ship cruise missiles (ASCMs) and small boats to improve the ship's self-defense capability. The Navy is studying the efficacy of laser weapon systems against these threat classes as a complement to existing kinetic weapons. While laser weapon systems provide several benefits to Navy ships, they are susceptible to environmental effects and have greater power requirements than available. Therefore, it is necessary to assess energy storage systems to meet these power requirements.

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LIST OF ACRONYMS

ACAF	Advanced Climate Analysis and Forecasting
ANCHOR	Atmospheric Naval Postgraduate School Code for High Energy Laser Optical Propagation
ASCM	Anti-Ship Cruise Missile
CIWS	Close-in-weapon system
COTS	Commercial-off-the-shelf
DIW	Dead in the Water
DTE	Detect to Engage
ExPERT	Extreme and Percentile Environmental Reference Tables
FAC/FIAC	Fast Attack Craft/Fast Inshore Attack Craft
FEL	Free Electron Laser
HEL	High Energy Laser
LaWS	Laser Weapon System
LEEDR	Laser Environmental Effects Definition and Reference
MATLAB	Matrix Laboratory
NSLOT	Naval Surface Layer Optical Turbulence
ONR	Office of Naval Research
PIB	Power-in-the-Bucket
RAM	Rolling Airframe Missile
SSL	Solid-State Lasers
SWAP-C	Size, Weight, Power and Cooling
TTI	Time to Impact
UAV	Unmanned Aerial Vehicles

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EXECUTIVE SUMMARY

Modern naval warfare is experiencing a shift in tactics and strategy that requires changes to the way the U.S. Navy is currently prepared to conduct war. Maintaining a large blue water fleet is no longer a requirement for dominating strategic sea lines of communication. New and abundant unmanned technologies make it easier for an enemy to overwhelm the capabilities of the traditional fleet. The Office of Naval Research (ONR) is investigating directed energy weapons, specifically high-energy lasers (HEL), to counter these emerging technological threats. Current ships do not have the capability to provide power directly to a HEL weapon system without causing power transients on the electrical bus. Therefore, there must be an energy storage system to power the HEL. A HEL has a magazine that is capacity constrained by both the size and the recharge rate of the energy storage system. This study seeks to determine the size of the energy storage system necessary for the HEL to counter the new asymmetrical warfare and swarm tactics employed by other countries. Additionally, this research examines the effects of visibility and the air/sea temperature difference on the size of the energy storage. The results of this research will help determine the important factors of size, weight, power, and cooling (SWAP-C) requirements for various energy storage methods. This research compares the size and weight of lead acid batteries, lithium-iron batteries and flywheels as well as examining strengths and weaknesses of each.

This research used a design and analysis approach to determine the amount of energy storage needed, the effects of visibility and air/sea temperature difference, and the size and weight of energy storage systems. In order to determine the energy storage needs, a model was created to simulate engagements of three types of targets. An examination of the Atmospheric Naval Postgraduate School (NPS) Code for High Energy Laser Optical Propagation (ANCHOR) code, developed by the NPS Physics Department, assisted in determining a method of integration into the model. Once the integration method was determined, a model was created to use the ANCHOR results to determine a dwell time for various threats. The three threats chosen were fast attack craft/fast inshore attack craft

(FAC/FIAC), unmanned aerial vehicles (UAV), and anti-ship cruise missiles (ASCM). Attributes such as speed, cruising altitude, material, etc., for each target was determined and used in conjunction with the ANCHOR code to determine a dwell time. The model also incorporated characteristics of the solid-state laser technology maturation (SSL-TM) program for the HEL used in the model. The laser and threat attributes were used with atmospheric data to determine a laser dwell time. The dwell time determines how much energy the HEL needs. Simulations were conducted to determine the amount of energy needed by the HEL to engage four types of attack: FAC/FIAC-only attack, UAV-only attack, ASCM-only attack and a multi-threat attack consisting of all three threats. The purpose of this testing method was to examine energy storage needs of the HEL if it was to engage a single-threat attack compared to multi-threat attack. The simulation ran 500 times for each threat or threat combination, and the energy storage and dwell times were averaged at the end for an analysis. For each threat type, multiple simulations were run varying the visibility conditions of the engagement and the difference between the air and sea temperature. This allowed for an analysis of how different atmospheric conditions affected the amount of energy storage.

During the start of testing, it was determined that the ASCM threats were unable to be destroyed by a 150 kW laser in a head on engagement. The decision was made to remove the ASCM threats from testing and instead consider a FAC/FIAC and UAV combined threat since there was no difference for energy storage using all three threats. The simulations used a 150 kW laser, with 25% efficiency, in the summer, in the Strait of Hormuz, with poor visibility (10 km). There are also numerous other constraints and assumptions for the HEL system, and the targets that were engaged, to produce the results. The simulations showed that the HEL requires an energy storage system of 200 MJ to counter FAC/FIAC-only and FAC/FIAC and UAV threat. The HEL system requires 80 MJ to counter a UAV-only threat. The difference comes from a combination of several factors; the materials used for each of the threats, the maximum engagement range of the HEL, and the atmospheric location of the threats. The results also showed that in good visibility, turbulence increases the amount of energy storage. However, when visibility is reduced the turbulence is less of a factor.

A 200 MJ lead acid battery storage system weighs 4,060 kg and occupies 1.9 m³ of space. A 200 MJ lithium-iron battery storage system weighs less at 600 kg and occupies 0.6 m³ of space. A 200 MJ flywheel energy storage system weighs 9,161 kg and occupies 1.18 m³ of space. The recharge time of lead acid batteries is hours, while the recharge time of lithium-iron is 1-2 hours and a flywheel requires a recharge time of seconds. Since the flywheels can be recharged very rapidly, a 200 MJ flywheel is not necessary. A 28 MJ flywheel with a weight of 1,200 kg and volume of 0.16 m³ is a viable option and competitive with other energy storage methods (Sylvester 2016).

This research establishes a framework for future research on energy storage and HEL performance. The model is adaptable and can incorporate cooling, a bigger variety of threats, specific types of energy storage, etc. The results also establish a reference point for energy storage needed. While the model showed that 200 MJ is required, that result comes with a long list of assumptions and should only be used as a reference and not as a final solution. Further work can improve the amount of storage needed and research can be done to reduce SWAP-C requirements of energy storage systems.

Reference

Sylvester, Jeremy E. 2014. "Power Systems and Energy Storage Modeling for Directed Energy Weapons." Master's thesis, Naval Postgraduate School.
<http://hdl.handle.net/10945/42734>.

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I. INTRODUCTION

The U.S. Navy is studying the use of directed energy weapons specifically a high-energy laser (HEL) to counter asymmetrical warfare tactics. The Office of Naval Research (ONR) is funding directed energy research with the purpose of developing and demonstrating the operational use of a laser weapon that improves the self-defense capabilities of U.S. Navy ships (Office of Naval Research [ONR] n.d.).

The HEL requires a large amount of power that the current ships cannot provide without overwhelming the electrical bus or causing an electrical transient when the laser is firing. Therefore, the HEL must have its own energy storage system. The HEL would have a large magazine (the energy storage system) and would need to recharge in order to replenish its “ammunition.” This allows the HEL to draw energy from the storage system, use it for the engagement, and then recharge the system once the laser is no longer in use.

The successful engagement of a target with the HEL depends on the characteristics of the HEL, the characteristics of the target, and the atmospheric conditions. A higher power laser leads to greater irradiance on the target and shorter dwell times. The thickness and type of material for a target determines the amount of irradiance and dwell time to achieve a “hard kill.” A hard kill is when the threat is physically damaged and thereby prevented from hitting its intended impact point. The HEL can also be used to make a “soft kill.” A soft kill is when the threat is disrupted from hitting its target without physically burning through the threat’s exterior surface. Soft kills are usually a result of irradiating a threat’s sensors or navigation system. Atmospheric conditions help determine the amount of irradiance delivered to the target and the effective range of the HEL.

This chapter first develops the guiding research questions that shaped the scope of the study. The research questions are followed by a discussion on why the military has invested so heavily in laser-based weapon technology and how it can shape naval warfare in the years to come. The chapter concludes with an overview of the different types of lasers and the state of laser technology.

A. RESEARCH OBJECTIVES

The first objective of this research was to establish the required amount of energy storage necessary to engage the three most prominent threats to ships in an asymmetrical warfare environment: fast attack craft/fast inshore attack craft (FAC/FIAC), unmanned aerial vehicles (UAVs), and anti-ship cruise missiles (ASCMs). Establishing an amount of energy storage is essential in determining the design aspects of a laser weapon system. The space available on a ship may limit the maximum size of the energy storage. If the HEL requires a more significant amount of energy storage to kill all the targets than the space available allows, this restricts the types of targets the HEL could engage.

The second objective of this research was to determine the effects that the uncontrollable environmental effects have on the performance of the HEL. Conventional weapons only suffer minor effects from environmental conditions that affect their usability. Their performance in poor weather conditions is not an issue. With laser weapons, the effectiveness of the laser is highly dependent on the operational environment, including atmospheric turbulence, humidity, and the presence of aerosols. For example, a laser operating in the North Atlantic may perform better than in the Persian Gulf due to the concentration of aerosols in the region. This study included the examination of how altering several environmental factors affected laser performance and energy storage needs.

The third objective of this research was to examine different alternatives for energy storage. Space and weight are limited on U.S. Navy ships, and the system should not take up any more space than is necessary. There are several tradeoffs when selecting an energy storage system. A large energy storage system can support more laser shots fired per engagement and longer dwell times. The negatives of a large storage system are that it requires a greater amount of space, weighs more, and takes longer recharge. This research examined the tradeoffs when determining the size of the energy storage system. The tradeoff study focused on the size, and weight of the different types of energy storage considered for a HEL.

This research used a quantitative analysis method to meet the outlined research objectives. A model was created and multiple simulations were conducted to assist in the determination of the size of the energy storage system. After an analysis of the results, the research concluded with recommendations for the amount of energy storage based on threat types. It also discussed the weaknesses in the model as well as areas for improvement, and areas of further research. The desired goal was to provide the U.S. Navy with useful information about energy storage requirements for HELs with respect to size, weight, power and cooling (SWAP-C) factors. The main contribution of this research is a model that can be used for further systems engineering and physics theses.

B. BACKGROUND

Throughout military history, the side that brought the largest and most advanced naval force to a battle often prevailed. Alfred Mahan captured this concept in 1892 when he wrote *The Influence of Sea Power on History* in which he advocated for large fleet on fleet actions. There are several cases where a smaller force was able to use natural chokepoints or maritime terrain to defeat a larger naval force but most large scale naval battles have been decided on the size and power of the fleet. Since the end of the Cold War, there has been no near-peer competitor to the U.S. Navy. The U.S. maintains the most aircraft carriers and the most advanced combat systems in the world. While there is no fleet that can withstand the full force of the U.S. Navy, an older type of threat has reemerged that challenges the strategies and tactics from the Cold War.

Countries that cannot afford to maintain or equip a large, technologically advanced fleet are relying on asymmetric warfare techniques to overwhelm the enemy. Iran learned the effectiveness of small boat operations during the final phases of the Iran-Iraq War. In 1988, Iran engaged the U.S. Navy with massed swarm attacks and suffered devastating losses (Nadimi 2006). However, Iran learned valuable insight into asymmetric warfare tactics that they have continued to develop. Instead of focusing on massed swarm attacks which are susceptible to air attack, the focus has shifted towards dispersed swarm attacks (Nadimi 2006). Since then, Iranian Naval doctrine has changed from major fleet operations to asymmetric warfare operations (Nadimi 2006). The Islamic Revolutionary Guard Corps

Navy and the Islamic Republic of Iran Navy continue to build a large fleet based on small vessels. While each individual vessel does not present a large threat, the combination of all vessels and the use of swarm tactics make the Iranian Navy worthy of consideration. These tactics can be adopted and adapted by any other nation seeking to deny the free and open use of the sea.

Countries that can afford expensive fleets are developing the swarm style tactics utilizing the emergence of new autonomous technologies like UAVs. Conventional tactics led to the development of highly advanced combat system suites such as Aegis, which can monitor and engage a large amount of threats. However, swarm tactics are designed to target and attack the limited ordnance supplies faced by all naval ships by overwhelming the opponent with quantity instead of quality. A large quantity of old slow missiles can be just as dangerous, if not more, than a couple new fast missiles. Older missiles are also cheaper and more accessible than some of the new types of missiles.

While the U.S. Navy has developed some tactics and methods to minimize the effectiveness of these styles of attack, the commanding officer must still decide whether to use a \$400,000 missile to defeat a single UAV or try to shoot it down with smaller caliber weapons. The U.S. Navy has developed better small caliber weapons that can accurately destroy incoming threats, but the amount of storage available for ammunition and the weight of the ammunition limit the abilities of the weapons. These emerging threats have created a need in the U.S. Navy for a weapon system that has a large ammunition capacity and a low cost per shot.

The addition of laser weapons enhances the lethality against different types of opponents and allows the United States to maintain the most formidable Navy in the world. A laser conserves limited ammunition supplies when the enemy has an abundance of expendable assets to use. While lasers provide an immense benefit to large-scale fleet on fleet engagements, they are a more valuable tool for swarm tactics. Since their invention in 1960, the military has continually researched lasers and laser-based weapons with moderate success.

C. MILITARY LASER DEVELOPMENT

Over the years, the military has considered three different types of lasers. The first type was chemical lasers. Chemical lasers “transform the energy stored in chemical bonds into a nearly monochromatic beam of coherent electromagnetic radiation or light” (Perram et al. 2010, 123). To create a chemical laser, supersonic nozzles mix various chemicals together. The chemicals create an exothermic reaction, which excites electrons in the elements to a higher energy state (Perram et al. 2010). The excited electrons then undergo spontaneous emission to produce light. The emitted light is stored in an optical cavity, which consists of two mirrors surrounding the exhaust gases (Perram et al. 2010). The light amplifies over many passes through the optical cavity via stimulated emission to create the laser beam (Perram et al. 2010). Figure 1 shows a simple diagram of how a chemical laser creates a laser beam.

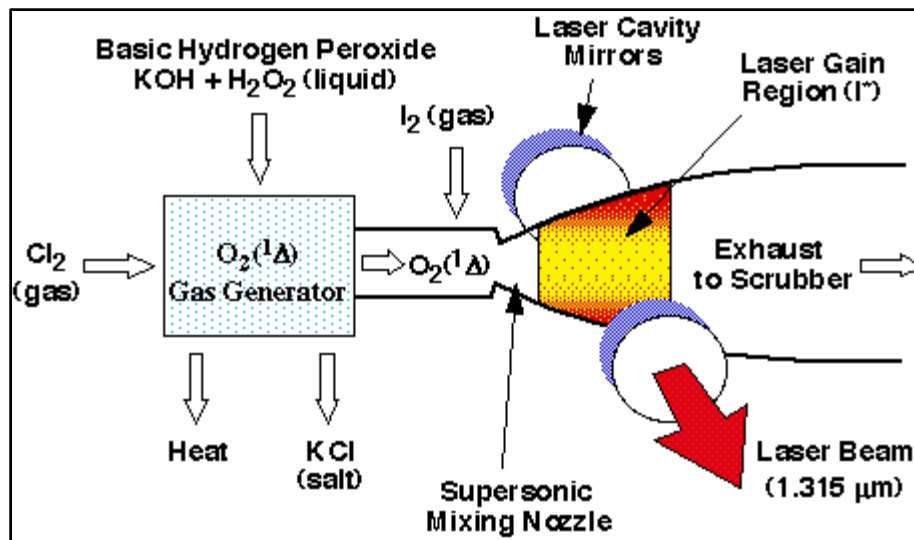


Figure 1. Chemical laser operation. Source: Kopp (2008).

Chemical lasers were the first type of lasers to have a power output exceeding 1 MW (Perram et al. 2010). They produce a good quality beam and they are mature in terms of technological development. The Tactical High Energy Laser and Airborne Laser both employ a chemical laser but they are not suitable for maritime use (Perram et al. 2010).

First, the chemicals and exhaust gases are highly toxic and unsafe in the close spaces of a ship. Also, the amount of chemicals available limits the number of “shots” for a chemical laser. The chemical lasers would then require special considerations for the storage and transfer of the chemicals used.

An alternative to chemical lasers is the free electron laser (FEL). FELs send a beam of unbound electrons from a particle accelerator through an alternating magnetic field called an undulator (Perram et al. 2010). The magnetic field causes the electron beam to wiggle and emit photons through spontaneous emission (Perram et al. 2010). The electrons in the field also interact with the light and the magnetic field of the undulator to create additional photons through stimulated emission (Perram et al. 2010). Figure 2 shows the operation of a FEL.

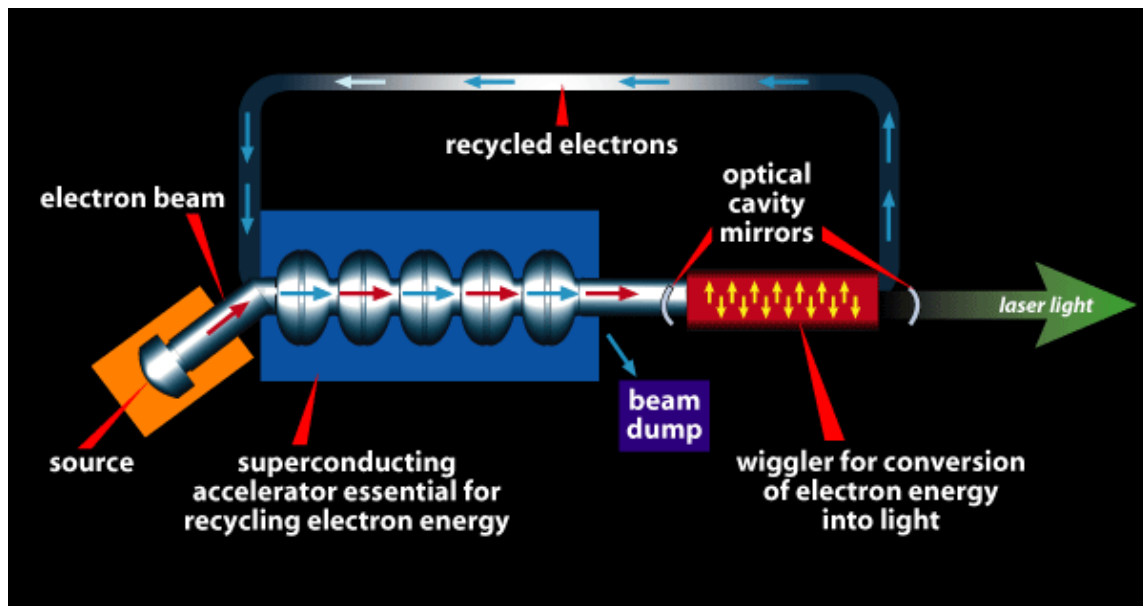


Figure 2. FEL operation. Source: Jefferson Lab (2007).

The benefit of FELs is that the operator can tune the electron beam or the undulator to create light at specified wavelengths to compensate for atmospheric attenuation. They are also energy efficient and provide an excellent quality beam over long distances (Perram et al. 2010). This would make them ideal for use against supersonic missiles since they can engage the missile earlier than other types of lasers. Additionally, there is no fixed gain medium to heat up. Therefore, the cooling requirements for FELs are less than other types of lasers. They have not been able to reach MW levels yet, but work is ongoing. The FELs require shielding from the radiation emitted by stray electrons (Perram et al. 2010). The size and weight of FELs does not scale with the output power. This makes the FELs large and heavy which may limit their usability on navy ships.

The final class of military lasers are solid-state lasers (SSLs). SSLs work by pumping electrical power into a solid gain medium (Perram et al. 2010). The atoms in that medium become excited. The atoms spontaneously release energy in the form of photons (spontaneous emission) (Perram et al. 2010). The photons reflect between two mirrors. The reflected photons excite more atoms, causing them to emit more photons, which are coherent with the original photons (stimulated emission) (Perram et al. 2010). One of the mirrors is semi-reflective allowing some of the photons to pass through thus forming a coherent laser beam (Perram et al. 2010). Figure 3 shows a simple diagram of an SSL using a fiber optic cable.

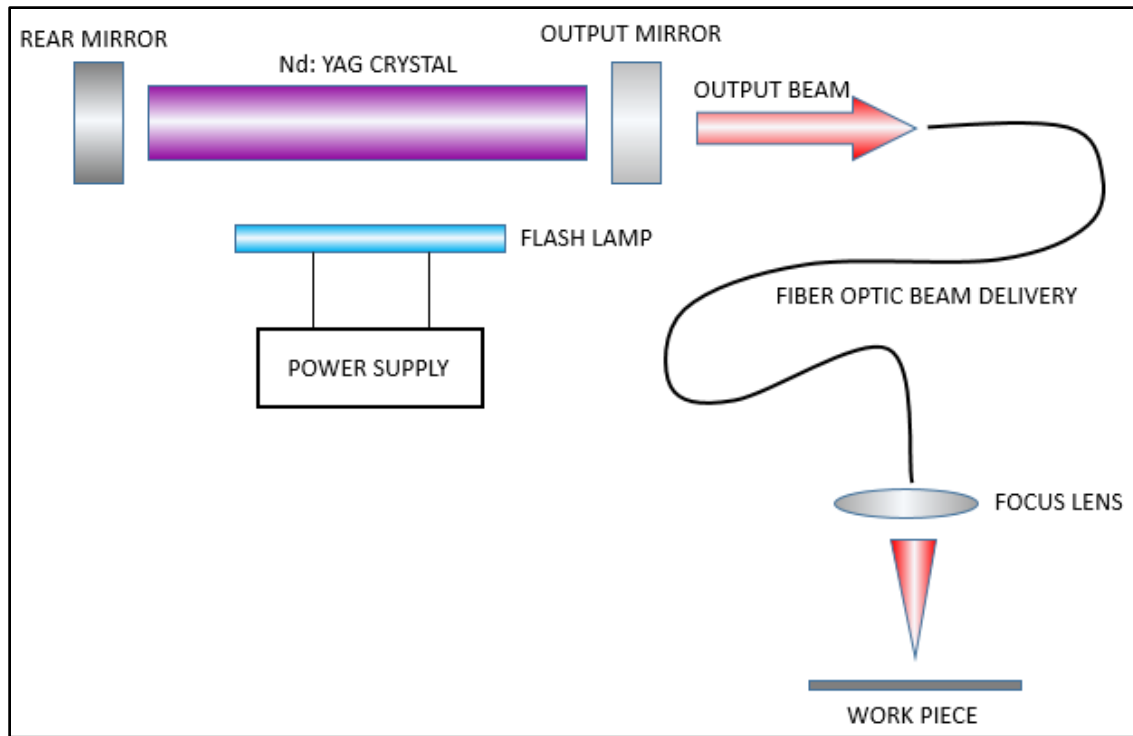


Figure 3. SSL operation. Source: II-VI Infrared (n.d.).

SSLs are compact, lightweight and most importantly do not release toxic exhaust or radiation, like chemical and free electron lasers (Perram et al. 2010). SSLs are limited in their power because of the low thermal conductivity of the glass or ceramic substrate (Perram et al. 2010). This also limits the laser to sub megawatt levels and creates waste heat that needs cooling by a standalone or ship system. However, SSLs are the preferred near-term solution, since they are widely used in industry. This means that there are many commercial-off-the-shelf (COTS) products for the U.S. Navy to use. By using COTS products, the U.S. Navy can reduce the overall price of the system and ensure that there are replacement parts readily available.

The U.S. Navy recently completed testing of their Laser Weapon System (LaWS) aboard the USS *PONCE* (AFSB(I)-15) shown in Figure 4.



Figure 4. LaWS on USS *PONCE* (AFSB(I)-15). Source: Hambling (2016).

The operational test showed the capability of a 30 kW laser to destroy a Scan Eagle UAV, to detonate rocket-propelled grenades on a small craft, and to disable a fast boat by destroying the boat engine (Bruce 2016). The tests were so successful that the USS *PONCE* stayed on station longer than planned to conduct further testing. A secondary benefit of the LaWS was that it provided the crew with enhanced surveillance and target identification abilities (Bruce 2016). The Chief of Naval Research stated that it is “almost like a Hubble telescope at sea” (Bruce 2016). The testing declared that HELs are operational and ready for use in the fleet. In early 2018, ONR announced that it planned to place an updated variant of the LaWS onboard LPD-17 class ship (Eckstein 2018). The laser will be “bolted on” and not integrated into the ships combat systems suite (Eckstein 2018). Additionally, Lockheed Martin received a contract in late January 2018 to install a High Energy Laser with Integrated Optical-dazzler and Surveillance onto a Flight IIA DDG-51 destroyer by fiscal year 2020 (Naval Today 2018). The U.S. Navy is constantly pursuing improved laser technology to increase the capability of surface combatants.

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II. LITERATURE REVIEW

With the successful test of the LaWS on the USS *PONCE*, military lasers are coming closer to rolling out to U.S. Navy ships. Since this technology is so new, there is not much literature about modeling the laser performance. Some of the literature that is available remains classified and is not available for distribution. Therefore, this chapter focuses on several topics that are important considerations in laser weapon modeling and development. This chapter starts with an overview of the effects of a maritime environment on the HEL performance. The chapter then proceeds to discuss the need for energy storage systems to integrate HELs onto U.S. Navy ships, as it is the focus of this research. The chapter concludes by outlining the systems engineering approach taken to research the objectives of this study.

A. ATMOSPHERIC EFFECTS ON LASER PERFORMANCE

A laser's ability to destroy an incoming target depends on the amount of irradiance (power density) that the laser can produce. The irradiance is dependent on the maximum output power and atmospheric effects such as extinction, thermal blooming and turbulence (Perram et al. 2010). Extinction can be broken down into absorption and scattering. As the laser beam travels to the target, the photons that comprise the beam interact with molecules and aerosols in the air: the main component being water molecules (Sprangle et al. 2004). Figure 5 shows the extinction coefficient of the atmosphere with and without the presence of aerosols.

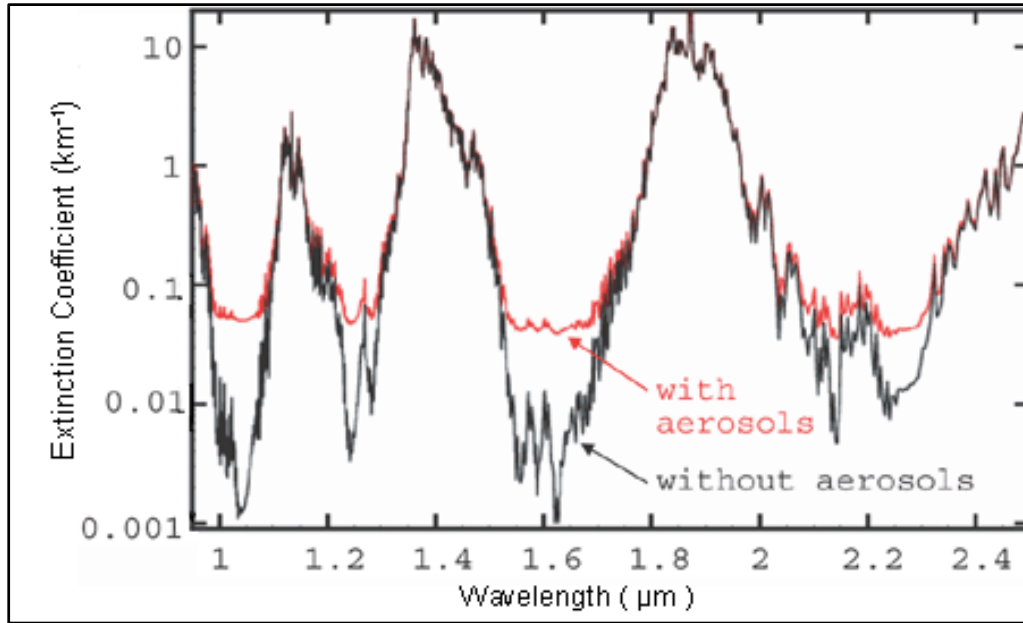


Figure 5. Extinction coefficient of atmosphere with and without aerosols.
Source: Sprangle et al. (2004).

Absorption occurs when molecules capture the passing photons, which may involve the release of a new photon at a lower energy level (Sprangle et al. 2004). Absorption is mostly dependent on molecular vibration/rotation lines of the absorbing molecule (Sprangle et al. 2004). Scattering occurs when the photons collide with molecules or aerosols and are re-emitted in a different direction. Scattering is mostly dependent on the wavelength of the beam (Sprangle et al. 2004). The amount of extinction of a laser beam depends on the particles in the air and the wavelength of the laser. Several “windows” provide more transparency and minimize the effects of extinction (Perram et al. 2010). Figure 5 shows several wavelengths where windows in absorption and scattering occur.

Thermal blooming is a byproduct of absorption. As the molecules absorb photons, there is an increase in temperature of the air along the beam path (Perram et al. 2010). The increase in temperature decreases the density of the air and thus its index of refraction, resulting in a lensing effect that causes the laser beam to diverge (Perram et al. 2010). As the beam spot size increases, its irradiance drops. This can also occur when there is wind present. If cool air flows across a beam, the air heats up and create the same divergent lens

effect (Perram et al. 2010). The laser beam ultimately bends into the direction of the wind. Thermal blooming is important because above a certain amount of laser output power, the irradiance of the beam on the target starts to decrease (Perram et al. 2010). There are several mitigations to reduce the effect of thermal blooming such as choosing a wavelength to reduce absorption, pulsing the laser beam to minimize heating the air along the beam path, or using multiple beam directors and combining the laser beam right before the target (Perram et al. 2010). Selecting a wavelength that best suits the atmospheric conditions can reduce some of these effects. A FEL can easily modify the wavelength produced, which is what makes them so attractive for shipboard use (Sprangle et al. 2004).

The last atmospheric effect is turbulence. Atmospheric turbulence is hard to predict. Fluctuations of the temperature and pressure of the air along the path of the beam create pockets of turbulent air (Perram et al. 2010). In a maritime environment, the difference between the temperature of the sea and the air can cause turbulence (Perram et al. 2010). The friction of winds from different directions interacting with each other can also create turbulence (Perram et al. 2010). Unlike thermal blooming, the random nature of turbulence creates scintillations (“twinkling”) in the beam (Perram et al. 2010). This leads to an irregular distribution of power at the targeted point (Valiani 2016). Each of these effects can have a negative impact on the irradiance at the target. Figure 6 shows a comparison of the beam spot with and without the effects of turbulence. The beam atop (with no turbulence) would have a much greater irradiance than the beam on the bottom (with turbulence). A HEL would require a longer dwell time on a target if the profile of the laser beam looked like the picture on the bottom.

To counter the effects of turbulence a new technology was developed called adaptive optics. A low power beam “samples” the atmosphere between the source and the target, and then a deformable mirror distorts the wavefront of the laser before it leaves the beam director to compensate for turbulence (Kopp 2008). Using thousands of tiny actuators, the mirror is continually distorted in new directions to provide a uniform beam onto the target’s surface (Kopp 2008).

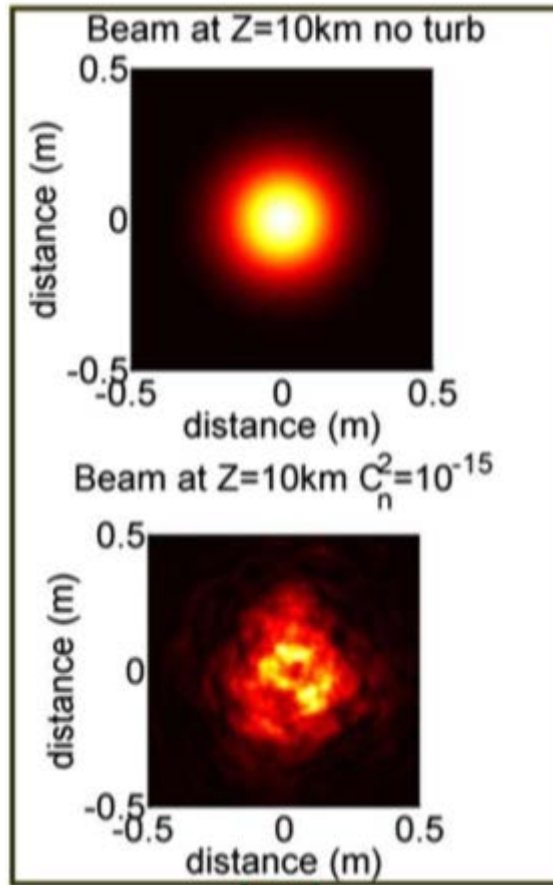


Figure 6. Laser spot with no turbulence and with turbulence.
Source: Brown, Juarez, and Brown (2013).

B. ENERGY STORAGE SYSTEMS

When designing the different classes of U.S. Navy ships, designers did not expect the ships to operate laser weapons. Many U.S. Navy ships lack the power required for a laser weapon or the space necessary for a generator dedicated to a laser weapon. Additionally, the power required during the operation of a laser could overwhelm the electrical bus and cause an electrical transient. This could shut down vital combat system operations. Installing an energy storage system on the ship is the most practical way to integrate laser weapons. When choosing a type of energy storage system to use, there are tradeoffs between the energy density and the power density. Figure 7 shows the energy and power density ranges for the most common types of energy storage systems.

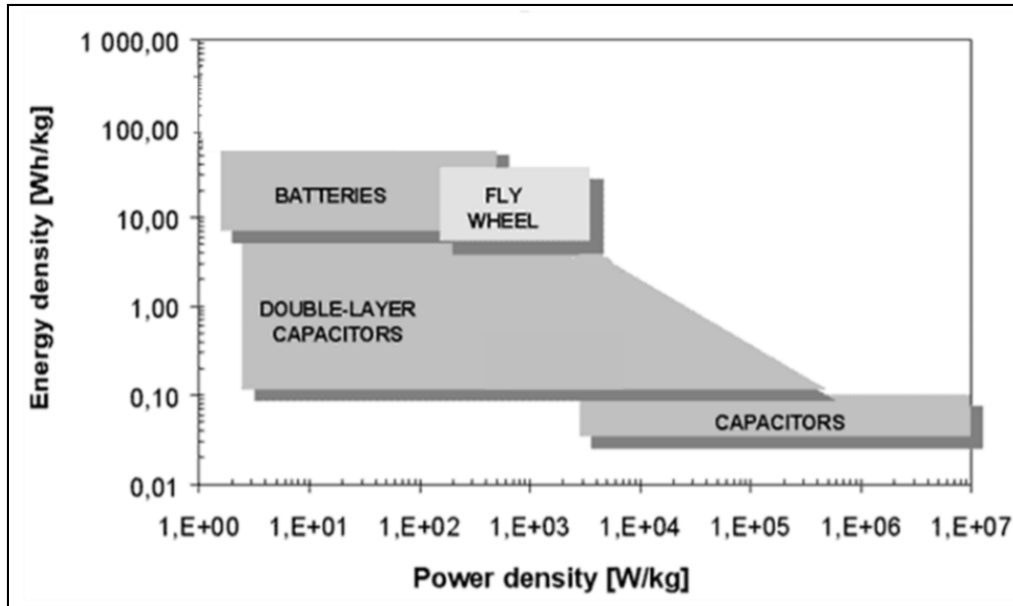


Figure 7. Energy density versus power density for various energy storage systems. Source: Lawson (n.d.a).

An attractive energy storage system for a U.S. Navy ship is a flywheel. Flywheels possess greater power density and roughly the same energy density as conventional batteries (Kuseian 2013). Flywheels store energy by converting electrical energy into kinetic energy. Modern flywheel systems utilize magnetic bearings and a magnetic field to rotate a rotor around an axis at very high speeds (Calnetix 2016). Charging the energy storage system starts with increasing the speed of the rotor to the maximum allowable speed. As energy is required from storage, the kinetic energy is converted back into electrical energy and the rotor slows as a result (Lawson n.d.,a). Flywheels are often much more efficient, reliable, and less costly than batteries. They also do not require any additional maintenance or replacement and can take up less space and weight (Calnetix 2016). The electromagnetic aircraft launch system onboard the FORD class of carriers utilizes a flywheel energy storage system, and flywheels have been proven as an uninterrupted power supply backup system (Doyle et al. 1995).

The major drawbacks to flywheels are that for the amount of energy storage that is required, the flywheel must be large and they are not available off-the-shelf. Since the

military would most likely be the only user of such large flywheels, the flywheel would be custom made and more expensive than other COTS options. As energy storage needs increase for HEL weapons, flywheel technology may advance to fill the role.

Batteries are the best near-term option for an energy storage system because they have high energy density and an acceptable power density (Sylvester 2014). The two prevailing types of batteries are lead-acid and lithium-ion. Lead acid batteries are more mature, safer and approved for large-scale shipboard use. Lithium-ion batteries are newer, lighter but not approved for widespread shipboard use due to their fire hazard potential. Lithium-ion batteries have faster charging times and better discharge tolerances than lead acid (Valiani 2016). Lithium-ion batteries have an energy density around 1000 MJ/m³, which is significantly higher than lead-acid batteries at 200 MJ/m³ (Valiani 2016). The higher energy density allows the energy storage system to take up minimal space at a reduced weight. Figure 8 shows the gravimetric versus volumetric energy density of the different types of chemical batteries.

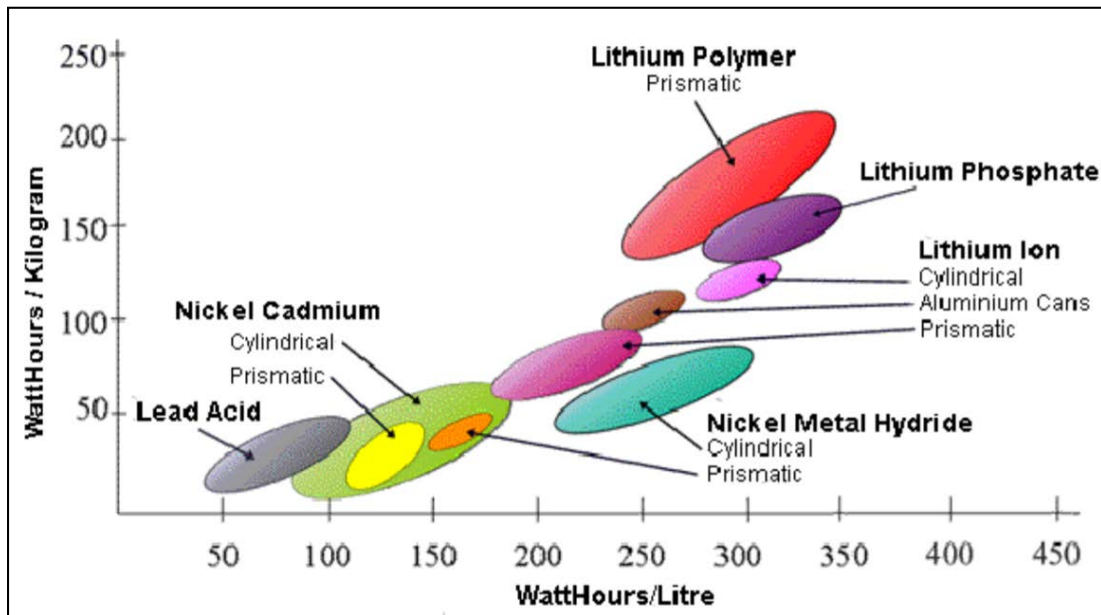


Figure 8. Energy density of various types of batteries. Source: Lawson (n.d.b).

A newer type of lithium battery that does not pose a significant fire hazard is the lithium-iron battery. Using iron phosphate for the battery cathode increases the thermal and chemical stability of the battery, which makes it safer for shipboard use (Newcastle Systems 2015). Lithium-iron batteries are a subcategory of the lithium phosphate batteries in Figure 8. If the batteries are improperly charged or discharged, they do not combust like lithium-ion batteries (Newcastle Systems 2015). However, the lithium-iron batteries are in the beginning stages of development and may take several years before their approval for large-scale use on U.S. Navy ships. Space and weight are in limited supply on most U.S. Navy ships, and it is vital to minimize these properties, while increasing the energy density so that the ship can place additional weapons on board or install new systems.

C. MODELING AND SIMULATION–BASED SYSTEM ENGINEERING APPROACH

Models and simulations are vital parts of the systems engineering process. The first step in the systems engineering process is to establish a need and identify stakeholders and their requirements (Blanchard and Fabrycky 2014). As the new system starts to take shape and system requirements and components start to integrate together, it is important to verify that the created system works according to design. Models and simulations provide a cheap and effective way to make a determination early in the design process if the system performs as desired (Maier and Rechtin 2009). The designers face two options if the system model cannot perform the basic requirements as determined by the stakeholders. The designers can go back and try to redesign the system to meet requirements or the designers can consult with the stakeholders to redefine requirements. Once a model/simulation has demonstrated the desired performance characteristics, the system can move to a more formalized testing phase (Blanchard and Fabrycky 2014). Creating models and conducting simulations frequently involves assessing how well the system is adhering to the design requirements. It is easier and more cost effective to change a part of the systems design than redesigning an existing system.

Models can take shape in many different forms, and have various levels of fidelity, from a simple engagement model to detailed physics-based models. Models usually benefit the project by providing a low cost alternative to building multiple prototypes for testing. The simulations can evaluate the performance in the models with well-known and established formulas. It is important to verify the results of the models through various means. This may include conducting initial tests of the system if available, using the model to predict results of comparable existing systems, or comparing models results to analytic predictions. The system can then implement changes, so that as the system moves to the prototyping phase, it has a greater chance of performing as desired. The prototype test results provide feedback to improve the model. The process of constant modeling, simulation and verification must continue throughout the entire design process. The effective use of modeling and simulation can save the project many of man-hours and dollars by ensuring the system performs as designed.

III. METHODOLOGY

This chapter discusses the approach used in this research to create and use a model to examine energy storage requirements. The chapter begins with an introduction to how the model was constructed and what tools were used to demonstrate the capabilities and limitations of the model. This also shows integration points of the model and allows further research to expand and refine the model. The chapter then outlines the general assumptions for creating the model to provide the reader with a better understanding of the constraints and areas of exploration in follow-on research. A discussion follows of the three major variable sets of the model: the controllable friendly variables, the uncontrollable enemy variables and the uncontrollable environmental variables. Each variable is examined and the reasoning behind the selection of inputs is discussed. The chapter then looks at the different outputs the model provides and explains how they are used in the analysis section. The chapter concludes with a broad overview of how the model was created before conducting an in-depth review of each of the steps of the model. This allows readers the ability to examine areas that can be used as integration points.

A. MODELING TOOLS

Three different types of tools created a model of the HEL engagement for this research. While further testing would be required to validate the HEL model, two of the three tools have been validated and used by various research groups working with the Department of Defense. Figure 9 is a context diagram that shows how the three tools are integrated to model HEL engagements.

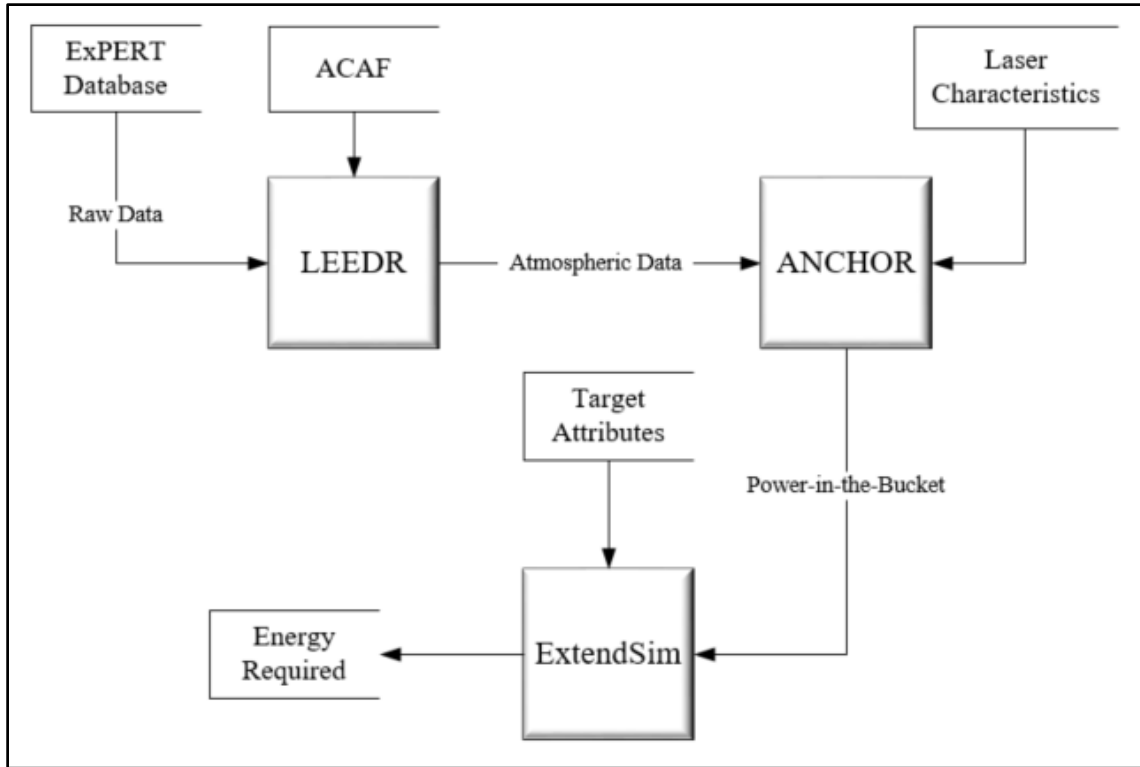


Figure 9. Context diagram of tools used to create HEL model

1. Laser Environmental Effects Definition and Reference (LEEDR)

LEEDR is a matrix laboratory (MATLAB) program created by the Air Force Institute of Technology. The program creates atmospheric profiles for any area in the world using the Extreme and Percentile Environmental Reference Tables (ExPERT) database and various atmospheric models. LEEDR has two primary purposes: “1) to create correlated, physically realizable vertical profiles of meteorological data and environmental effects...; and 2) to allow graphical access to and export of the probabilistic data from the ExPERT database” (Fiorino and Schmidt 2017). The program allows users to enter a location, atmospheric data, clouds and precipitation, laser specifications, and specific ground conditions. Data from the U.S. Navy Advanced Climate Analysis and Forecasting (ACAF) system can supplement the pre-defined values in LEEDR. After all inputs are entered, the program outputs a MATLAB data file. The program also allows users to create graphs and plots of the calculated data. Figure 10 shows the user input interface.

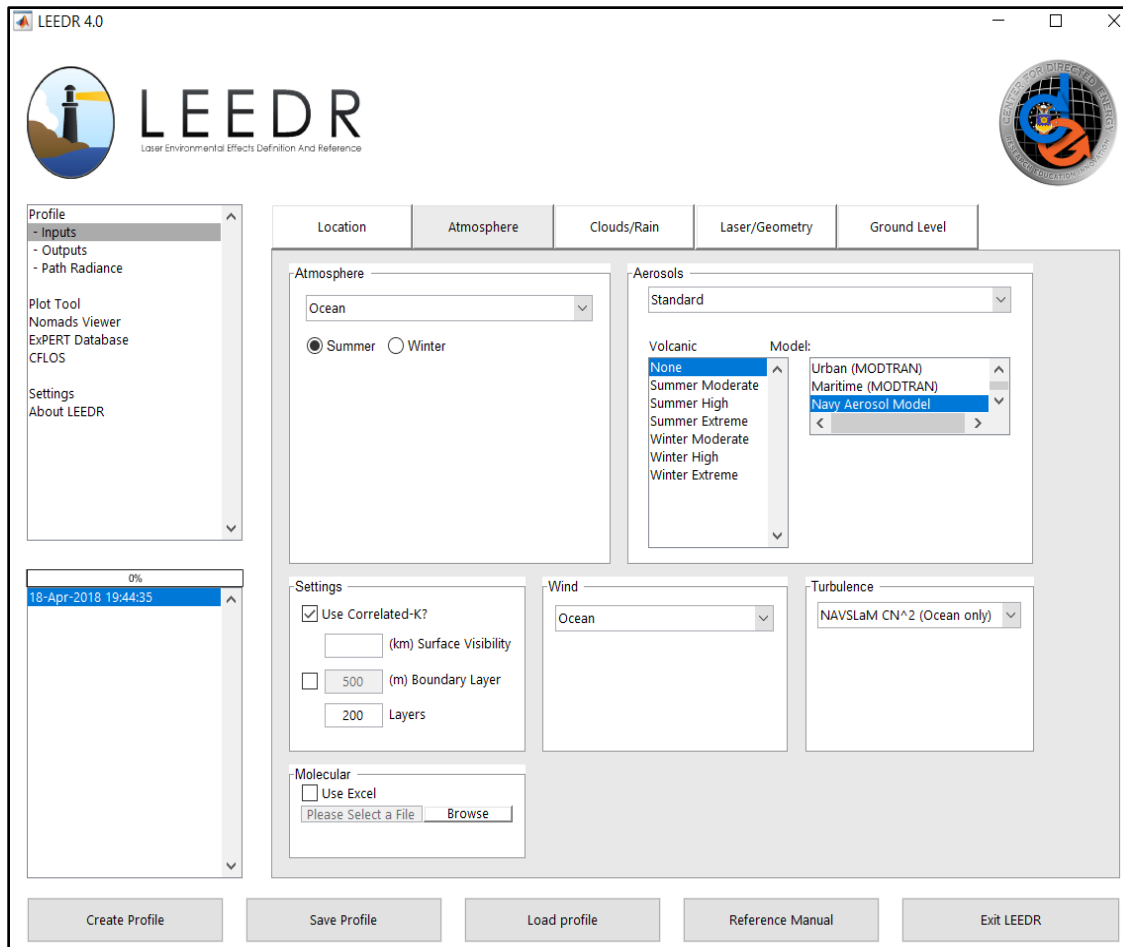


Figure 10. LEEDR user interface. Source: Fiorino and Schmidt (2017).

2. Atmospheric Naval Postgraduate School Code for High-Energy Laser Optical Propagation (ANCHOR)

ANCHOR is a code developed by the Directed Energy Physics Group at the Naval Postgraduate School. ANCHOR is MATLAB based and conducts tens of thousands of iterations of initial conditions with scripted code. ANCHOR uses the data table generated from LEEDR as input for atmospheric conditions. ANCHOR then produces data plots and data tables for the laser irradiance, power-in-the-bucket (PIB), and dwell time with respect to range and altitudes. The PIB is the amount of irradiance within a defined area or “bucket.” Excel uses the PIB data table to determine the dwell times when engaging targets. The dwell-time data produced by ANCHOR assumes that the target is stationary and does

not take into account the linear motion of the target. This research looks at a number of targets with varying kinematics; therefore, Excel, using PIB values from ANCHOR, calculates the dwell times.

3. ExtendSim and Excel

ExtendSim is a modeling software tool that allows for discrete or continuous modeling. Users can create dynamic real-world processes and analyze how specific factors influence the system (Imagine That Inc. 2007). This study used ExtendSim to create a model of a detect-to-engage (DTE) sequence that is commonly used in U.S. Navy combat systems. An Excel workbook was embedded into ExtendSim to use data from ANCHOR to calculate dwell times based on the altitude, range, speed, and type of material of the target. While ExtendSim could handle calculations, it was found to be very challenging, so Excel was used as a better intermediary between ANCHOR and ExtendSim to perform the calculations.

B. ASSUMPTIONS

When creating models and running simulations, it is important to determine the assumptions of the model. Models cannot determine how a system performs every time, but can give a reasonable expectation of performance. Numerous factors (environmental and technical) may limit performance. Models can also determine integration points for a future system or can be further refined to show patterns in the systems behavior. Testing the system validates the results of the model and allows for refinement. The results of each operational test improves and revalidates the model. The modeling assumptions used for this research were:

1. Linear Motion

The HEL platform has no linear motion. During a swarm attack, U.S. Navy ships use special maneuvers to gain the tactical advantage. The worst case is that the ship has suffered an engineering casualty and has become dead in the water (DIW).

2. Altitude Variation

The FAC/FIAC and ASCM in the model remain at constant altitudes. FAC/FIAC have almost no change in altitude except the changes due to sea state. The change is minimal (less than 1m) and therefore negligible. ASCMs change altitude based on predetermined flight patterns. These flight patterns are classified, so the model assumed that the altitude remained constant and that the ASCM struck the LPD at the initial launch height of the ASCM. The UAV starts at an initial altitude and the altitude decreases proportionally to the decrease in range, such that if the UAV were to hit the LPD, it would be at the waterline of the vessel where the damage would be most severe. Since UAVs are new technology, it is difficult to determine how an adversary will employ them against surface vessels. The assumption for a constant decreasing altitude and range represents the worst-case scenario, since any deviation from this trajectory would allow for more time for an engagement. For example, if a UAV was to loiter in a particular area, it allows the HEL more time to engage. While the ASCM could follow a similar descending path, the cruising altitude of the ASCM is so low that the effects are almost negligible. Figure 11 shows the different attack paths each of the targets flying/sailing towards the LPD in the model.

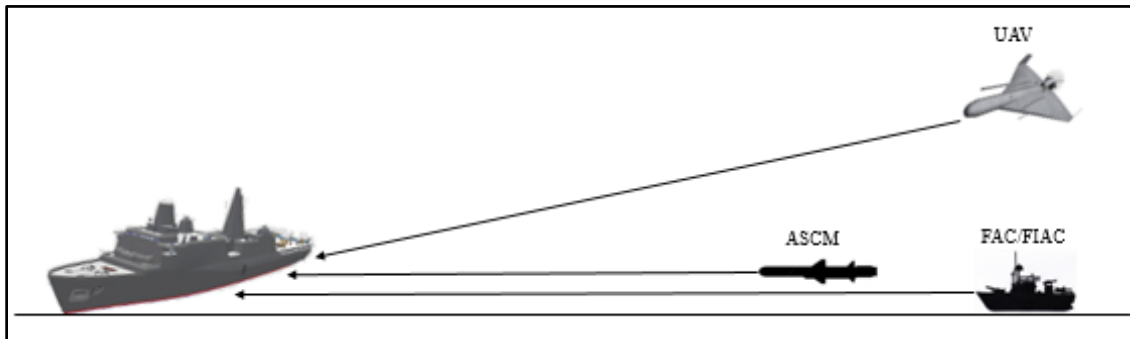


Figure 11. Attack profiles on ASCM, UAV and FAC/FIAC

3. Target Headings

All targets head directly inbound to the LPD. If the LPD is DIW, the targets head directly to the LPD. This also ensures the shortest distance traveled by the targets since a maneuvering ship adds relative distance to the path of the targets. The relative distance would give the HEL system time to engage more targets. The shortest distance tests the HEL in the worst-case scenario. Furthermore, a directly inbound target is the worst case for the effect of thermal blooming on an HEL engagement. A crossing shot engagement provides “new” air which is cooler than the air along the beam path.

4. Target Generation

Targets appear at random intervals. Before engaging any vessel/aircraft, U.S. Navy ships must determine hostile intent. A ship/aircraft on a collision course does not always constitute hostile intent. In this model, the “creation” of the target occurs when the ship determines the hostile intent of the target. This means that all targets are within the detection range of the LPD and properly identified. While the LPD may have a limited detection range, shipboard assets (helicopters) and off ship assets (other ships) can greatly extend the detection range.

5. Target Engagement

The HEL engages only one target at any one time. The purpose of the model is to determine both the amount of energy storage needed by a single HEL system and the operational limits of the HEL. Multiple HEL systems on a ship increase energy storage and operational limits linearly with each system added.

6. Minimum Time to Impact

The HEL system does not engage a target with a time to impact (TTI) less than ten seconds for ASCMs, and less than three seconds for UAVs and FAC/FIAC. If a new target appears that has a TTI of less than three seconds, the HEL would have to clear any target it is currently engaging, slew to the new target, and engage. This process would most likely result in the HEL not being able to engage the target quick enough. In that case, the combat

system would hand off the target to other ship systems for last-minute engagements by the close-in-weapons system (CIWS) or rolling airframe missile (RAM). The ten seconds provides time for the ship systems to engage the ASCM. While the model does not simulate CIWS or RAM engagements, the systems require a minimal time before engaging a high-speed threat. FAC/FIAC and UAVs are significantly slower; therefore, the minimum TTI is lower for FAC/FIAC and UAVs than the minimum TTI for ASCMs.

7. Maximum Engagement Time

The HEL system has a maximum engagement time of ten seconds. A solid-state HEL system cannot lase a target for long periods because of the heating of the lasing medium. Long periods could exceed the capacity of the cooling system and cause damage to the system. The maximum engagement time depends on the cooling system that supports the HEL. This research uses the 10-second maximum to serve as a single shot, but acknowledges that this could be longer. If the first shot does not kill the target, the target returns to the queue so that the HEL can reengage the same target with another shot until it kills the target or until the target is inside minimum engagement range. Any damage done with the first shot does not compound with the second shot or subsequent shots. Engaging the same target multiple times accounts for HELs capable of longer maximum dwell times.

8. Kill Assessment

The kill assessment is instantaneous. If the energy deposited, as calculated by Excel, exceeds the defined amount of energy for a kill, the model considered the target destroyed. This leads to the instantaneous kill assessment. In an operational environment, there is a delay as an operator determines the destruction of a target.

9. FAC/FIAC Engagements

Successful engagement of a FAC/FIAC results in a mission kill. The weapons and systems on each FAC/FIAC vary. In real-world operations, an operator would need to determine the best way to destroy an incoming FAC/FIAC. To keep the model simple, each successful engagement of the FAC/FIAC prevents it from being a further threat.

10. Autonomous Engagement

The HEL engages all targets autonomously without any operator delay time. Real-world employment of weapon systems usually requires a minimum of one person to authorize each engagement. This adds an additional delay to the system. The additional delay may limit the amount of engagements, which limits the maximum energy storage size. A system with no delay allows the testing to determine what would be the maximum energy storage size. Further testing that includes operator delay could refine the storage size.

11. FAC/FIAC

The model uses FAC/FIAC attributes of the Iranian Peykaap III class vessels. These vessels are fast, small, very maneuverable and similar to other types of FAC/FIAC used by other countries.

12. UAV

The model uses UAV attributes of the Israel Aerospace Industries Harpy. The Harpy is a UAV designed to loiter in an area to search for, and then attack, a specific target (Jane's by IHS Markit 2018a).

13. ASCM

The model uses ASCM attributes of the C-802 sub-sonic missile. This is an older style missile, but one that still presents a threat to the U.S. Navy, as they are widely available.

C. FRIENDLY FORCES VARIABLES

The friendly forces variables are the variables over which the U.S. Navy has direct control. Each of these variables was selected based on existing system capabilities or designed capabilities of a specific system. These variables are the only known variables in the model and, therefore, do not change. If additional capabilities or improvements change variables, the user of the model is able to implement the changes.

1. HEL Slew Rate

The HEL slew rate is the angular velocity of the beam director. To engage targets, the beam director must slew to their azimuth, which adds a delay to the engagement process. The unit of measure is degrees per second. According to Brij Agrawal (email to author, April 19, 2018) the slew rate an HEL is 100 degrees per second.

2. HEL Power

The HEL power is the nominal output power of the weapon system. The unit of measure is kilowatts. This value is determined from the SSL system, which is scheduled for installation on the LPD-17 class. These simulations use a 150 kW laser.

3. HEL Azimuth

The HEL azimuth is the direction that the beam director is pointing, relative to the ship. The azimuth changes only when the beam director slews to a target. After the engagement is complete, the beam director stays at the last known azimuth. The unit of measure is degrees. The simulation starts with the azimuth at 0 degrees and changes based on the azimuth of the incoming targets.

4. Platform Height

The platform height is the height above the waterline where the beam director is located. The height of the beam director affects HEL performance. A beam closer to the water is more prone to extinction due to aerosols and to distortion due to turbulence. The unit of measure is meters. The platform height value is an input in ANCHOR only, and was determined from a list of possible installation areas on the LPD 17. These simulations use a platform height of 10 m.

5. Beam Director Diameter

The beam director diameter is the diameter of the lens of the HEL. The beam director serves to focus the HEL on the target that it is engaging. Normally, a bigger lens allows for a more focused beam. A focused beam is desirable to increase the irradiance

(power per unit area) at the target. The director diameter size is limited by physical constraints and by the Fried parameter. The Fried parameter characterizes the turbulence of the air along the beam path. The more turbulence in the air, the smaller the Fried parameter. If the beam director diameter is greater than the Fried parameter, the benefit of the larger director diameter is lost because of the turbulence. The beam director diameter should be as large the system allows, but should not exceed the Fried parameter since anything greater than that parameter is a waste of material and resources. A tradeoff analysis determines the ideal beam director diameter. A beam director with a diameter greater than about 50 cm is impractical for shipboard use. In this research, the beam director diameter is set to 30 cm, which comes from the SSL technology maturation system design.

6. Laser Wavelength

The laser wavelength is the distance between crests on the waves of light that emit from the laser. Lasers emit a group of coherent photons traveling with the same wavelength. Laser wavelength is important when discussing attenuation. There are certain wavelengths that are less prone to attenuation than others, as shown in Figure 5. These wavelengths are ideal since they retain a majority of their power as they travel to the target. The HEL system in the model uses a laser with a wavelength of 1.06 μm . This wavelength is typical for SSLs and falls within an attenuation window.

7. Laser Beam Quality

The laser beam quality, or M^2 , quantifies the variation of the laser from an ideal Gaussian beam. Equation 1 determines the beam quality by measuring the divergence and beam waist of the laser:

$$M^2 = \frac{\theta \pi w_0}{\lambda} \quad (1)$$

In the equation, θ is the beam divergence, λ is the wavelength of the laser and w_0 is the beam waist radius. If a laser has an M^2 value of one, the laser is operating in a single Gaussian mode, also known as TEM₀₀ mode. As the beam's divergence increases, the M^2 increases, which results in less power in the bucket. Less power in the bucket could result

in a failure to kill the target. The laser represented by the model has an assumed beam quality of $M^2 = 3$, which is a reasonable value for a high power SSL.

8. Beam Type

Beam type describes the profile of the laser irradiance at the exit of the beam director. The two main beam types are Uniform and Gaussian. A Uniform beam deposits energy evenly across the beam director. A Gaussian beam has a higher energy deposit at the center and decreases farther away from the center of the beam. A Uniform beam is favorable in HEL design because it reduces the peak irradiance on the beam direction, and it is easier to achieve with beam combining technology. A beam combiner is necessary for fiber lasers to reach a power of 150 kW. The model uses a laser with a Uniform beam.

9. Size of the Bucket

When determining the effects of a laser against a specific target, engineers identify a specific area of the target where the laser must deposit a majority of its energy. This area is the bucket, which is assumed to be circular in nature. The size of the bucket is the radius of this circular area. A simplistic assumption is that any energy deposited outside this area is lost. In reality, the energy deposited outside the area could potentially aid in the destruction of the target. This is hard to determine, since the area surrounding the bucket may contain a variety of materials or be at a different distance. The model assumes a bucket size of 5 cm. This would adequately damage the flight dynamics of typical airborne threats and would cause serious concerns to small boats, depending on the location.

10. Jitter

The jitter is the root mean square variation of the angle of the laser due to vibrations of the platform holding the laser and/or the pointing and tracking error. Most conventional weapon systems provide some sort of dampening system and active alignment to reduce their vibration, which keep their shots accurate. Lasers require enhanced vibration reduction, since the slightest shift off the intended axis could result in missing the target, depending on the distance. This value is determined experimentally based on the ability of

the dampening of the system. The laser represented in this model has a jitter of 5 micro radians.

11. Laser Efficiency

The laser efficiency is the ratio of output power of the laser over the amount of input power to the laser. The low thermal conductivity of the substrate leads to the creation of heat in SSLs. This waste heat comes from the initial power supplied to the HEL. Typical HEL efficiencies range from 20 to 30%. This means that the HEL needs 500 to 750 kW power input to have a nominal output of 150 kW, and the remaining 350 to 600 kW is lost as waste heat, which means the laser must be cooled to prevent overheating. Lasers in development for U.S. Navy testing must provide their own cooling. Therefore, the laser efficiency includes the power lost to cooling as well. This thesis treats cooling as part of the system that the energy storage system feeds. Determining if installed cooling systems could support a laser weapon system requires further study. The model uses a laser efficiency of 25%.

12. Engagement Range

The engagement range of each type of target derives from the performance of the HEL against the material of the target and the operating environment of the HEL. When selecting the engagement range for the HEL model to use, the first step was to run an ANCHOR model in a specified area. The ANCHOR model produced a table of the PIB given a specified range and altitude. Table 1 shows a sample of ANCHOR output data for the PIB of a 150 kW laser operated in July in the Strait of Hormuz with good visibility. ANCHOR also generated a color map of PIB versus altitude and range, shown in Figure 12.

Table 1 PIB versus target altitude (columns) and range (rows) for a 150 kW laser with good atmospheric conditions during July in the Strait of Hormuz

	Power-in-the-Bucket (kW)				
Altitude/Range (m)	10	400	800	1200	1600
1.00 ^a	150	149	148	146	145
200	149	149	147	146	145
400	149	148	147	146	145
600	148	148	147	146	145
800	148	147	147	146	145
1000	147	147	147	146	145
1200	147	147	146	146	145
1400	147	146	146	146	145

^aThe altitude starts at a height of 1 m to allow for the targeting of FAC/FIAC.

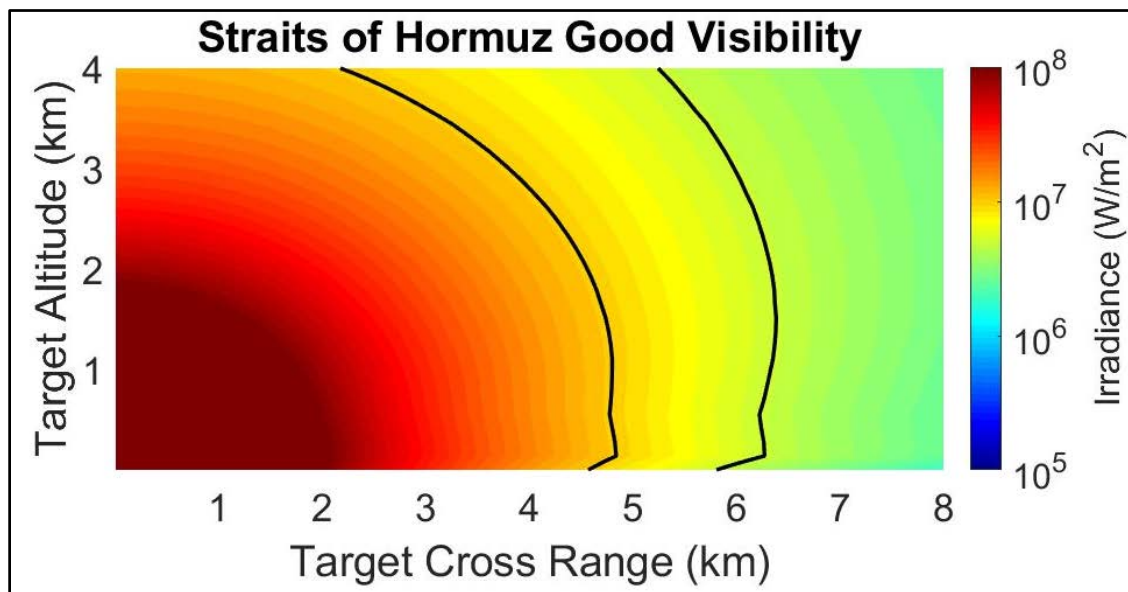


Figure 12. ANCHOR color map of PIB versus target altitude and cross range in Strait of Hormuz with good visibility

The PIB is the amount of power that arrives at the target within a specified area, taking into account diffraction and atmospheric losses. Since ANCHOR measures PIB in units of watts (joules per second), the model calculates the dwell time by dividing the energy required to kill the target by the PIB. Doing this assumes that the target is stationary, which is rarely the case. As the target closes the distance to the HEL, the PIB increases. Therefore, the model determines the PIB each time the target moves closer. A simple way to examine this is to use a step process. Given a target speed of 70 m/s, the UAV decreases the range by 63 m and the altitude by 31 m towards the HEL every second. The model had to use bilinear interpolation to determine the PIB at each step since the range and altitude of the UAV did not match the values produced by ANCHOR. Excel calculated the PIB for each step using ANCHOR data and target kinematics. Table 2 shows the PIB, calculated through bilinear interpolation, as the UAV closes the distance to the HEL with range and altitude decreasing accordingly.

Table 2 PIB of an approaching UAV with a speed of 70 m/s.

Altitude (m)	Range (m)	Power-in-the-Bucket (kW)
1000	2000	144
969	1937	144
937	1875	144
906	1812	144
875	1750	145

The change in PIB is not very noticeable in Table 2 since the power is decreasing in watts instead of kW. The PIB data from ANCHOR does not consider the power losses at the target due to conduction and radiation. Equation 2 determines the power lost at the target due to the heat conduction of the material (P_{cond}):

$$P_{cond} = kA_{cond} \frac{T_{melt} - T_{Ambient}}{\Delta r} \quad (2)$$

where k is the thermal conductivity of the material, A_{cond} is the surface area over which the conduction occurs, T_{melt} is the melting temperature of the material, $T_{Ambient}$ is the initial temperature of the material (assumed 300 K), and Δr is the distance the temperature

gradient radiates away from the target area (assumed $\Delta r = 3$ cm). Equation 3 determines the power lost at the target due to the heat radiation off the material (P_{rad}):

$$P_{rad} = \varepsilon \sigma A_{rad} (T_{melt}^4 - T_{Ambient}^4) \quad (3)$$

where ε is the emissivity of the material, σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W/m²-k), and A_{rad} is the cross-sectional area of the target or spot size of the laser ($A_{rad} = 7.85 \times 10^{-3}$ m²). In addition to the conduction and radiation losses, the material reflectivity also causes power loss to the target. Equation 4 determines the power loss due to the reflectivity of the material (P_{refl}):

$$P_{refl} = P_{bucket} \Gamma \quad (4)$$

where Γ is the coefficient of reflectivity, and P_{bucket} is the initial PIB. At each specified range and altitude, each loss contributes to a reduction of the PIB. Equation 5 determines the absorbed power P_{abs} to account for the losses due to reflectivity, radiation, and conduction:

$$P_{abs} = P_{bucket} - (P_{refl} + P_{cond} + P_{rad}) \quad (5)$$

Table 3 lists the variables for each material used in the model. From these values the absorbed power was calculated.

Table 3 Material properties to calculate absorbed power

Material Type	k (W/(m-K))	A_{cond} (m ²)	T_{melt} (K)	ε^a	Γ^a
Aluminum (FAC/FIAC) ^b	210	6.28×10^{-4}	934	0.09	0.85
Aluminum (UAV) ^b	210	9.42×10^{-4}	934	0.09	0.85
316 Stainless Steel (ASCM) ^c	17	1.57×10^{-3}	1673	0.63	0.7

^aValues compiled from Engineering ToolBox (n.d.).

^bThermal conductivity and melting temperature complied from MatWeb (n.d.).

^cThermal conductivity and melting temperature complied from AZoM (2001).

Table 4 shows an example of the absorbed power versus target range and altitude of the UAV. While the power lost due to conduction and radiation remain constant, the power lost due to reflectivity increases as the initial power increases. This is why the power loss increases as the target gets closer to the HEL. The model assumes that the reflectivity at the target remains constant. In reality, the reflectivity decreases as heat starts to deform the surface of the target and make it less reflective.

Table 4 Absorbed power versus range and altitude of UAV

Altitude (m)	Range (m)	Absorbed Power (kW)
1000	2000	15.9
969	1937	15.9
937	1875	15.9
906	1812	16.0
875	1750	16.0

UAV target made of 2cm thick aluminum.

Excel then calculates the deposited energy from the initial PIB, the absorbed power, and the change in time that occurs as the UAV moves closer. Tables 2 and 4 give the PIB and absorbed power as the range and altitude of the UAV decreases at a constant angle, with the relative speed of 70 m/s. Multiplying the absorbed power by the change in time for each range and altitude combination gets the absorbed energy at the target. The change in time for each range and altitude combination is 1 second. Table 5 shows the absorbed energy of the UAV at each step based on the material properties defined in Table 3.

Table 5 Amount of energy absorbed by a target over a 1 sec time interval at each specified range and altitude

Altitude (m)	Range (m)	Absorbed Energy at Target (kJ)
1000	2000	15.9
969	1937	15.9
937	1875	15.9
906	1812	16.0
875	1750	16.0

Size of the bucket is 5cm for 150 kW HEL.

Using a one-second time interval essentially eliminates any additional calculations. The total energy absorbed is the sum of the energies absorbed at each interval. As soon as the sum of the absorbed energies exceeds the minimum required energy to kill the target, the engagement is complete. The dwell time of the engagement is the total number of 1-second steps the HEL needs to lase the target to exceed the energy required for the kill. If the summed energy does not exceed the energy to kill the target, the engagement has failed.

Excel, generates a plot that shows the engagement times for a UAV starting at any range or altitude based on fixed material type and speed. Figure 13 shows a MATLAB plot of the engagement times generated by Excel for a UAV, with a 2 mm thick aluminum skin, with a speed of 70 m/s, in the Strait of Hormuz in July, with good visibility, and air temperature equal to sea temperature. The range of the target varies from 10 m to 8,000 m and the altitude varies from 1 m to 4000 m. Figure 14 shows a similar plot, but the engagement times are for poor visibility; all other attributes remained the same.

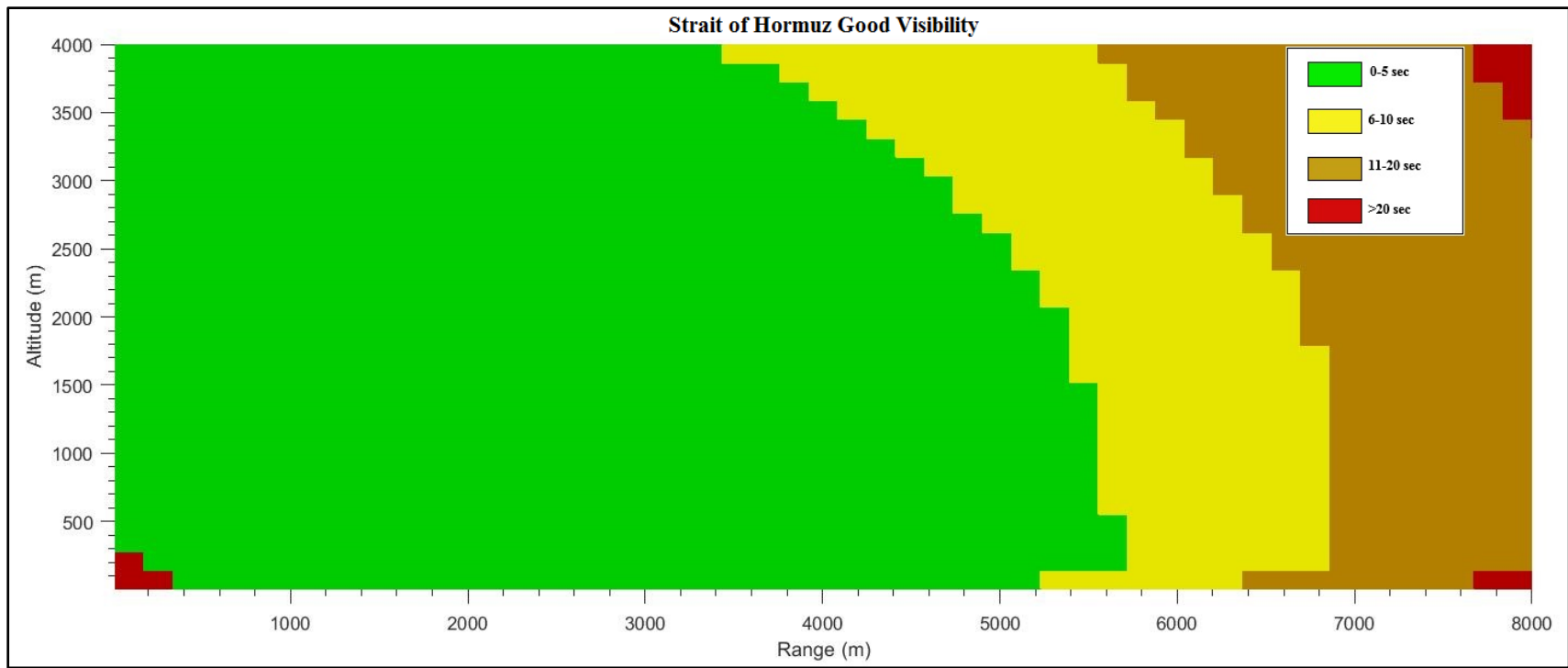


Figure 13. Laser engagement times for a UAV, 2 mm thick aluminum, speed of 70 m/s

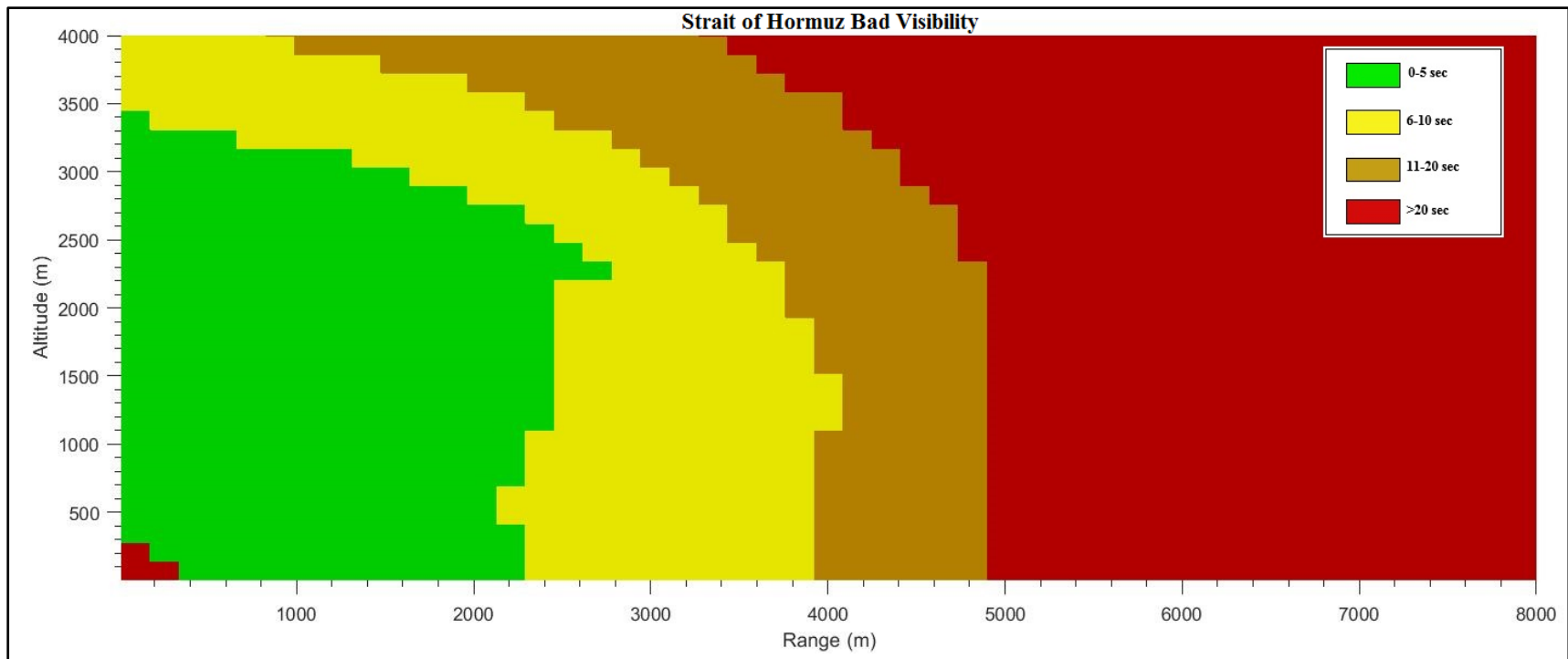


Figure 14. Laser engagement times for a UAV, 2 mm thick aluminum, speed 70 m/s

In both the figures, any engagement starting in the green area of the plot shows that the laser achieves a kill between 0 and 5 seconds. The yellow area is 6 to 10 seconds, the gold area is 10 to 20 seconds and the red area shows a dwell time exceeding 20 seconds. While the plots show engagement times greater than 10 seconds, the model breaks any engagement over 10 seconds and places the target back into the queue for reengagement. This limit was established due to cooling concerns of the laser but the maximum dwell time is adjustable if the cooling can support longer dwell times. The darker red areas located in the lower left hand corner of the plots is where the HEL was able to engage but could not kill the target before the target impacted the LPD.

Figures 13 and 14 demonstrate one of the major problems when trying to determine the engagement range. A 5000 m engagement range would allow for quick destruction of targets in Figure 13, while it would lead to extremely long dwell times in Figure 14. Looking at similar figures for each threat and material, in different locations, at different times of the year and in different visibility show the engagement range varying each time a variable changes. Other considerations are whether it is better to wait until the target comes closer before initiating the engagement, to reduce dwell time or engage the target as far away as possible. The closer a FAC/FIAC gets to the ship the greater chance it could fire off a missile that could strike the ship. However, engaging the FAC/FIAC closer reduces the dwell time and, hence, the amount of energy expended for the kill.

The decision of the engagement range is an extremely tough one. The problems presented above show that more research and discussion on tactical employment of lasers must occur before providing a realistic engagement range. Therefore, this research set the engagement range to 5000 m for all threats. This allows for the quick engagement of ASCMs, since their average initial range is within the engagement range. This also allows for most of the FAC/FIAC and UAVs to generate just outside the engagement range.

D. ENEMY VARIABLES

The enemy variables are the variables over which U.S. forces have no control. In order to keep this research unclassified, general assumptions and estimates were made

concerning the various attributes and characteristics of the enemy order of battle. The more accurate these variables are, the greater the accuracy of the model. The variables listed below are based on the selection of the type of FAC/FIAC, UAV and ASCM listed in the assumptions section.

1. Speed of FAC/FIAC

The speed is the rate at which the FAC/FIAC is closing the distance to the LPD. The unit of measure is meters per second. The Peykaap III has a max speed of 27 m/s (Jane's by IHS Markit 2018b). Moving at the maximum speed reduces the range of the Peykaap and the sea must be very calm to achieve the maximum speed. Sea conditions and other factors could lead to the Peykaap closing the target at a speed less than the maximum. The lowest speed assumed for this model is 50% of the maximum. Therefore, the model generated a speed based on a uniform distribution between 13 and 27 m/s.

2. Altitude of FAC/FIAC

The altitude is the height of the specific area onboard the FAC/FIAC, measured in meters, that the HEL targets. The location that would provide for the mission kill varies on each unique type of FAC/FIAC. Since the area varies, the model used an altitude of 1 m as the location where a hole burned into the hull provides enough damage so that the FAC/FIAC is no longer a threat.

3. Range of FAC/FIAC

The range is the distance from the HEL platform that the FAC/FIAC has shown hostile intent. The unit of measure is meters. The FAC/FIAC has a mean range of 6000 meters and a standard deviation of 1000 meters. While hostile intent can be determined farther out, generating a large number of targets outside of the engagement range of the HEL only increases the model run time. From initial analysis of the HEL, the irradiance exhibits a significant drop off beyond 6000 m due to diffraction and atmospheric losses. FAC/FIAC generate in or just outside the engagement range to speed up the modeling time. The model generated a range based on a normal distribution.

4. Energy for FAC/FIAC Kill

The energy for FAC/FIAC kill is the amount of energy that is necessary to burn through the material to produce a mission kill. FAC/FIAC can be disabled or killed in a multitude of ways. The HEL can destroy the engine, burn a hole through the hull, or ignite explosives onboard. A series of equations determines the energy for a FAC/FIAC kill. Equation 6 determines the energy needed to heat up the material (Q_1):

$$Q_1 = C_p (T_{melt} - T_{Ambient}) \rho V \quad (6)$$

where C_p is the specific heat capacity of the material, T_{melt} is the melting temperature of the material, $T_{Ambient}$ is the initial temperature of the material (assumed 300), ρ is the density of the material, and V is the volume of the material. Equation 7 determines the energy needed to melt the material (Q_2):

$$Q_2 = \Delta H_{Fusion} \rho V \quad (7)$$

where ΔH_{Fusion} is the latent heat of fusion for the material and ρ and V remain the same from the previous equation. Equation 8 derives from the combination of both of the equations to determine the total energy required to heat and melt the material (Q_{melt}):

$$Q_{melt} = Q_1 + Q_2 = \{C_p (T_{melt} - T_{Ambient}) + \Delta H_{Fusion}\} \rho V. \quad (8)$$

The Peykaap III is assumed to have an aluminum hull with a thickness of 3 mm (Jane's by IHS Markit 2018b). The exact hull thickness for the Peykaap III is not available to the public. The thickness of 3 mm is found on smaller fishing boats and is the same thickness as aluminum fuel tanks (Sorensen 2009). Table 6 and 7 list the material properties and energy to kill the FAC/FIAC.

Table 6 Material properties for FAC/FIAC. Adapted from MatWeb (n.d.).

	C_p (J/(g K))	T_{melt} (K)	$T_{Ambient}$ (K)	ΔH (J/g)	ρ (g/cm ³)
Aluminum	0.90	934	300	387	2.95

Table 7 Energy of kill for FAC/FIAC with given material thickness

Thickness (mm)	Aluminum (kJ)
3.00	66.5

While this model assumed a constant material and thickness for FAC/FIAC, the model can accommodate additional materials and thicknesses to simulate a wide variety of targets.

5. Speed of UAV

The speed is the rate at which the UAV is closing the distance to the LPD. This represents the distance traveled in a straight line towards the LPD and not the horizontal distance traveled by the UAV. The unit of measure is meters per second. The Harpy has a maximum speed of 70 m/s (Jane's by IHS Markit 2018a). The maximum speed limits the loiter time of the UAV. The model assumed the Harpy has a minimum speed of 35 m/s, which is half the maximum speed. Therefore, the model generated a speed based on a uniform distribution between 35 and 70 m/s.

6. Altitude of UAV

The altitude is the initial height of the UAV. The unit of measure is in meters. The Harpy has a maximum altitude of 3000 meters (Jane's by IHS Markit 2018a). While the controller programs the flight altitude of the Harpy, the model assumed the Harpy to have a minimum altitude of 1500 m. Therefore, the model generated an altitude based on a uniform distribution between 1500 and 3000 m. The UAV proceeds on a descending path at a constant rate such that the impact point on the LPD is at an altitude of 0 m. Figure 11 shows the flight profile of the Harpy.

7. Range of UAV

The range is the distance from the HEL platform that the UAV has shown hostile intent. The unit of measure is meters. The UAV has a mean range of 6000 meters and a standard deviation of 1000 meters. While hostile intent can be determined farther out, generating a large number of targets outside of the engagement range of the HEL only

increases the model run time. From initial analysis of the HEL, the irradiance exhibits a significant drop-off beyond 6000 m, due to diffraction and atmospheric losses. UAVs generate in or just outside the engagement range to speed up the modeling time. The model generated a range based on a normal distribution.

8. Energy for UAV Kill

The energy for UAV kill is the amount of energy that is necessary to burn through the material to enable a mission kill. Any damage to the UAV affects the aerodynamics and stability, which would cause a mission kill. The energy is determined using Equations 6, 7 and 8. The Harpy is assumed to have an aluminum exterior with a thickness of 2 mm. The actual thickness is not available in the public domain but it is similar to the standard skin thickness of a Boeing 757 (Werfelman 2011). Table 8 and 9 list the material properties and energy to kill the UAV.

Table 8 Material properties for UAV. Adapted from MatWeb (n.d.).

	C_p (J/(g K))	T_{melt} (K)	T_{Ambient} (K)	ΔH (J/g)	ρ (g/cm ³)
Aluminum	0.90	934	300	387	2.95

Table 9 Energy for UAV kill with given material thickness

Thickness (mm)	Aluminum (kJ)
2.00	44.4

While this model assumed a constant material and thickness for the UAV, the model can accommodate additional materials and thicknesses to simulate a wide variety of targets.

9. Speed of ASCM

The speed is the rate at which the ASCM is closing the distance to the HEL platform. The unit of measure is meters per second. The speed of the C-802 is 0.9 Mach

(Pike 2011). Given standard atmospheric data, this is approximately 300 meters per second. The speed of the ASCM only varies as the ASCM accelerates out of the launcher. The ASCM speed remains a constant in the model at 300 m/s.

10. Altitude of ASCM

The altitude is the height of the ASCM as it flies toward the HEL platform. The unit of measure is in meters. The C-802 travels at a constant altitude of 20 meters (Pike 2011). The altitude can change based on a specified flight profile, but that information is classified. The ASCM altitude remains a constant in the model at 20 m.

11. Range of ASCM

The range is the distance from the HEL platform that the enemy launches the ASCM. The unit of measure is meters. The ASCM has a mean range of 4000 meters and a standard deviation of 2000 meters. The FAC/FIAC launch ASCMs at close range to minimize flight time and increase the likelihood of a kill. The model generates a range based on a normal distribution.

12. Energy for ASCM Kill

The energy for an ASCM kill is the amount of energy that is necessary to burn through the material to enable a mission kill. Any damage to the ASCM affects the aerodynamics and stability, which would cause a mission kill. The energy is determined using Equations 6, 7 and 8. The model assumes the C-802 has a stainless steel nose cone with a thickness of 5 mm. The actual information is not available in the public domain, and nose cones are made out of special composite materials. Stainless steel was selected for its high melting temperature and density. Table 10 and 11 list the material properties and energy to kill the ASCM.

Table 10 Material properties of ASCM. Adapted from AZoM (2001).

	C_p (J/(g K))	T_{melt} (K)	$T_{Ambient}$ (K)	ΔH (J/g)	ρ (g/cm ³)
316 Stainless Steel	0.53	1673	300	285	8.08

Table 11 Energy for ASCM kill with given material thickness

Thickness (mm)	316 Stainless Steel (kJ)
5.00	321

While this model assumed a constant material and thickness for the ASCM, the model can accommodate additional materials and thicknesses to simulate a wide variety of targets.

13. Azimuth

The azimuth is the line of bearing, relative to the ship, from which the target proceeds toward the HEL platform. The unit of measure is degrees. The input values generate an azimuth after each target has been generated based on a uniform real distribution, since targets could come from any direction with equal possibility. This is representative of a dispersed swarm attack that Iran uses (Nadimi 2006).

14. Maximum Number of Targets

The maximum number of targets is the number of units that the ExtendSim model generates of a specific type. Since large-scale asymmetric warfare has not been used in recent history, it is necessary to study the strategies and tactics of current practitioners, such as Iran. Iran displays its tactics by state-sponsored propaganda of major naval exercises. During the Iranian exercise Great Prophet 9, the Iranians built a mock-up of a U.S. aircraft carrier and proceeded to conduct an attack (Rawnsley 2015). As seen in several YouTube videos, Iran attacked the stationary and defenseless carrier from multiple directions with more than 40 FAC/FIAC (Persian_boy 2015). The FAC/FIAC launched several missiles at the carrier, while some even pulled alongside the carrier and detonated explosives onboard (Persian_boy 2015). Iran has also demonstrated the use of UAVs in maritime operations (Rawnsley 2015). It is likely that asymmetrical attacks will incorporate UAVs as the technology becomes more prevalent and gets cheaper to produce. For example in Syria, unknown forces attacked Russian forces with a homemade UAV laden with explosives (Reid 2018).

The purpose of the model is to determine the energy storage of a single HEL laser against a large threat. The HEL never operates in an isolated environment and there are other shipboard systems to provide additional support. For that reason, there is a maximum of 30 FAC/FIAC, 20 UAVs and 5 ASCMs. These numbers were selected because they are above the reasonable expectations for a single weapon system to engage.

15. Arrival Time

The arrival time is the time when the combat system on the LPD determines hostile intent. In a swarm attack, all units would attack near simultaneously, but it takes the combat system time to locate, acquire, and classify each of the incoming targets. Since the targets attack near simultaneously, their arrival is assumed to be an exponential distribution. The exponential distribution ensures that the arrival time is not negative. The defined value is the mean of the arrival time. The unit of measure for the arrival time is seconds. This model uses a mean arrival time of a quarter of a second.

E. ENVIRONMENTAL VARIABLES

The model considers a range of visibility and atmospheric conditions in a given location, based on climatological data from the LEEDR database. While the enemy could use visibility to exploit weaknesses of the U.S. Navy, this thesis seeks to determine the size of the energy storage needed for the HEL in only a few select visibility conditions. The environmental variables during the use of a laser weapon always remain uncontrolled. While friend and enemy variables can be readily estimated, the weather is unpredictable even with the best model available. The weather variables are also important since they have a significant effect on the laser's capability as discussed above.

1. Location

The first variable that must be examined is where the HEL is expected to operate. Since 70% of the Earth's surface is water, there are too many places to possibly study. In order to limit the scope of the research, an area must be chosen that is the most likely area for an attack on U.S. vessels.

The Strait of Hormuz is one of nine strategic chokepoints around the world for shipping traffic. These chokepoints are critical to the shipping of oil as well as other materials throughout the globe (Bender 2017). Closing or blocking a single strait may result in longer shipping times, which translates into high prices for commercial goods and oil. The largest chokepoint is the Strait of Hormuz with approximately 17 million barrels of oil passing through on a daily basis (Friedman 2017). The Strait of Malacca is second with 15.2 million barrels daily (Bender 2017). To ensure that these straits remain open and the flow of shipping traffic remains unimpeded, the U.S. maintains a naval presence in or nearby and must be able to fight in the confined areas of the straits. The straits are perfect areas to employ asymmetric warfare tactics therefore; therefore, this research examines the HELs performance in the Strait of Hormuz.

2. Air and Sea Temperature

The difference between the air temperature and sea surface temperature can create turbulence, which has an effect on the HEL beam. Unless specified, LEEDR assumes that the air and sea surface temperatures are near equal. LEEDR does not allow the user to change the sea temperature but does allow the user to change the air temperature. The difference between the air and sea temperature was determined using the ACAF database. The air temperature was then adjusted in LEEDR accordingly. The air temperature reached a maximum of 1.6 degrees Fahrenheit above sea temperature and a minimum of 0.8 degrees Fahrenheit below sea temperature.

3. Atmosphere

The atmosphere determines the amount of aerosols in the air, and the level of turbulence. Atmospheric data such as temperature, wind, humidity, etc., differs depending on location. LEEDR uses numerous measurements to provide an approximation of atmospheric conditions at different times during the year. The model examined an HEL deployed to the Strait of Hormuz. In the model, the summer atmospheric data assisted in determining the most effective size of the energy storage system.

4. Aerosol Model

As previously discussed, the aerosols in the atmosphere cause attenuation of the laser. It is important to choose an aerosol model that best models the aerosols in an ocean environment. This research used the Global Aerosol Data Set to determine the aerosols over the ocean. This data set was chosen based on recommendations from Steven Fiorino at his presentation on the capabilities of LEEDR (Fiorino and Schmidt 2018).

5. Turbulence

Turbulence causes scintillations and an irregular distribution of energy at the target. The U.S. Navy developed the Naval Surface Layer Optical Turbulence (NSLOT) model to examine the effects of turbulence on transmission of electromagnetic signals. The model is now useful in determining the effects of turbulence on laser beams. This research uses NSLOT to provide an accurate model of turbulence in an ocean environment.

6. Visibility

The visibility of an area depends on the amount of dust and water molecules in the air. When greater amounts of water molecules are present, they collect on dust particles creating hazy conditions. This haze reduces the PIB at the target. The visibility is adjusted in LEEDR by manipulating the “multiplier” for the aerosol model. Good visibility (approximately 38 km) has a multiplier of 0.7, moderate visibility (approximately 28 km) has a multiplier of 1, and bad visibility (approximately 10 km) has a multiplier of 3 (Fiorino and Schmidt 2017).

F. MODEL OUTPUTS

The outputs from the model are the variables that were examined and used to make a determination about the size of the energy storage. The output variables listed below are the ones that have been deemed the most important in this area of study. Additional variables can be taken from the model but they do not contribute to the size of energy storage.

1. Total Dwell Time

The total dwell time is the amount of time that the HEL engaged all targets. Each target is limited to a maximum 10-second engagement time per attempt by the HEL. If the HEL fails to destroy the target on the first attempt and it is still far enough away, the model inserts the target back into the engagement queue. This means that the HEL could engage a single target multiple times. Therefore, the maximum dwell time possible is larger than just the number of targets multiplied by the maximum engagement time. The unit of measure is seconds. The total dwell time assists in determining the amount of energy used by the HEL. The model also displays the average dwell time to kill all of the targets per data run.

2. Targets Destroyed

The targets destroyed are the number of targets that the HEL system successfully killed. This does not include how many times the HEL fired at any particular target to achieve the kill. This value is for informational purposes and only shows that a laser would be successful against a given number of targets.

3. Targets Not Destroyed

The targets not destroyed is the number of targets the HEL failed to kill. This occurs due to a combination of factors such as the target's initial range, incoming speed, altitude, material properties or poor weather. This value is for informational purposes only and would only show when the HEL is reaching its operational limit in engaging targets.

4. Total Energy Used

The total energy used is the amount of energy that the HEL system uses during the engagement of all targets. Using Equation 9 the total energy used (E_{Total}) is calculated:

$$E_{Total} = \frac{t_{TD} P_{HEL}}{\eta_{HEL}} \quad (9)$$

where t_{TD} is the total dwell time, P_{HEL} is the HEL power, and η_{HEL} is the HEL efficiency.

The model provides the total energy used for each engagement at the end of an attack. The unit of measure is in kilojoules unless otherwise stated.

5. Number of Shots

The number of shots is how many times the HEL fired during each run. If a target is not killed after an engagement, it is recycled back into the queue for another shot. The number of shots shows if the HEL had to use multiple engagements or was unable to engage targets.

G. MODELING THE ENGAGEMENT

The first step in creating the model was to determine the desired outcomes of the model. Through discussions with stakeholders and advisors, the model was created to provide a recommendation on the size of the energy storage needed to operate an HEL against swarm attacks. Since size, weight, power and cooling are all valuable resources onboard ships, a HEL system must provide the best performance with the lowest impact to each of the four areas. In order to provide the size of the energy storage system, the model needed to determine how much energy would be used in combat situations. Therefore, the desired output of the model would be the amount of energy used by the laser during each engagement.

Before constructing the model, a top-level diagram was created to identify the capabilities and functions for the model. A top-level diagram identifies each step of the model and any external systems that the model uses. Figure 15 shows the top-level diagram designed for the creation of the HEL engagement model.

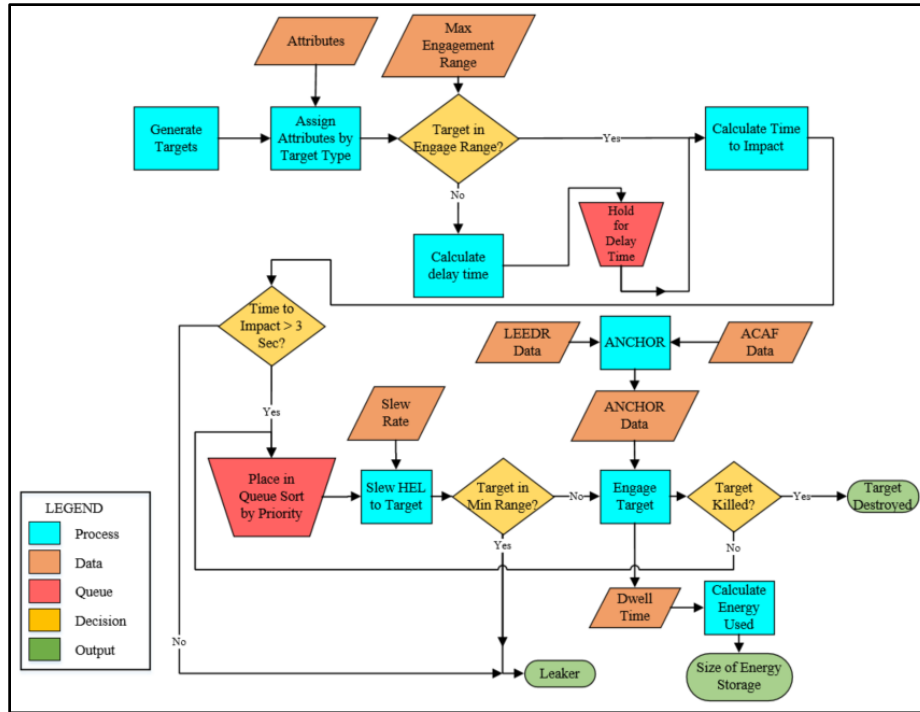


Figure 15. Top-level diagram of HEL engagement model

The model was then constructed based off the top-level diagram. Testing the model during the construction process ensured that it operated as designed.

There were many variables used in creating the model that if changed would affect the results. This research focused on three specific variables: the type of threats, the visibility, and the difference in the air and sea temperature. Many of the enemy attributes were randomly assigned. To reproduce the appropriate distribution accurately, the model was run 500 times for each possible combination of variables. Table 12 shows the test matrix used during this research.

Table 12 HEL test matrix

Simulation Number	FAC/ FIAC	UAV	ASCM	All Threats	Good Visibility	Moderate Visibility	Bad Visibility	High Air Temp	Neutral Air Temp	Low Air Temp
1	X				X			X		
2	X				X				X	
3	X				X					X
4	X					X		X		
5	X					X			X	
6	X					X				X
7	X						X	X		
8	X						X		X	
9	X						X			X
10		X			X			X		
11		X			X				X	
12		X			X					X
13		X				X		X		
14		X				X			X	
15		X				X				X
16		X					X	X		
17		X					X		X	
18		X					X			X
19			X		X			X		
20			X		X				X	
21			X		X					X
22			X			X		X		
23			X			X			X	
24			X			X				X
25			X				X	X		
26			X				X		X	
27			X				X			X
28				X	X			X		
29				X	X				X	
30				X	X					X
31				X		X		X		
32				X		X			X	
33				X		X				X
34				X			X	X		
35				X			X		X	
36				X			X			X

H. THE EXTENDSIM MODEL

The ExtendSim model follows a basic DTE sequence that is similar to a DTE on U.S. Navy vessels and outlined in Figure 15. The model allows the user to enter the type and number of targets desired. The first step of the model creates the targets that attack the HEL system. Each target has a unique arrival time that indicates when hostile intent of the target was determined. The model assigns specific attributes to the target based on previously discussed distributions. The model then conducts a check to determine if the target has reached the engagement range of the HEL. Figure 16 shows the section of the model that calculates whether the target is within the engagement range.

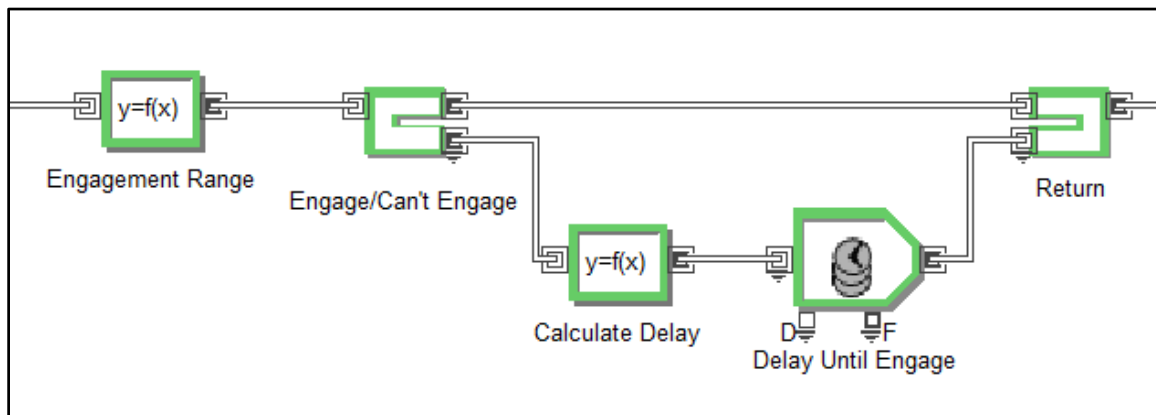


Figure 16. Engagement range check section of ExtendSim model

If the target is within the engagement range, it proceeds along the top branch of the model. If the target is not within the engagement range, it proceeds to the lower branch. The lower branch uses the speed, birth time, and range to determine how long it takes the target to reach the engagement range. The target is delayed the appropriate amount of time and added back to the main path. The model then calculates the TTI of the target and filters out targets that do not have at least a 3-second (or 10-second for ASCMs) engagement time. Figure 17 shows this portion of the model.

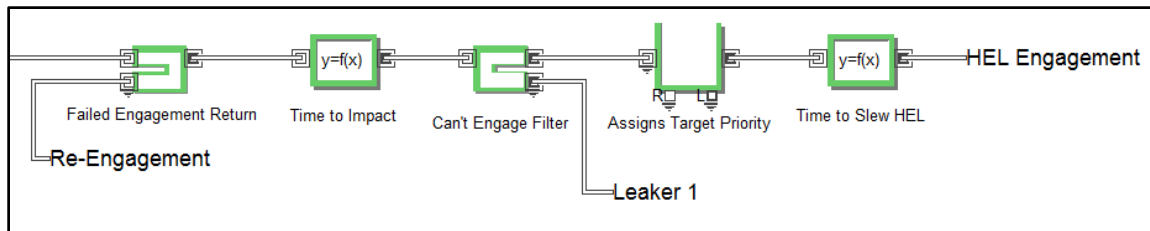


Figure 17. TTI calculation and filter section of ExtendSim model

Just prior to calculating the TTI there is a merge section. If the HEL does not successfully kill the target after the engagement, the target arrives back into this section of the model. This allows the HEL another attempt to kill the target. Any target with a TTI less than 3 seconds exits the model. The minimum engagement time of 3 seconds comes from the assumptions listed above. All targets with a TTI of 3 seconds or greater proceeds to a queue that assigns a priority to the target based on the TTI. The targets exits the queue in order of the priority assigned and proceeds to calculate the time necessary to slew the HEL towards the threat.

The next section of the model is where the targets are “engaged” by the HEL. Since the HEL can only engage one target at a time, the targets proceed to a gate that opens only when there are no targets in the specified section of the model, shown in Figure 18. After the target enters the engagement gate, the target waits for the HEL to slew toward the direction based on the earlier slew time calculation. Afterwards, the model calculates a current range of the target by using the current time in the model, the birth time of the target and the speed of the target. A target less than the minimum engagement range immediately exits the engagement section and the model records the target as not killed. A target greater than the minimum engagement range targeted enters then exits a holding queue. The queue does not add any additional time to the simulation. The queue activates a trigger for the next block. When tripped, the model reads the altitude, current range, speed and type of the target. The model writes these values into an imbedded Excel workbook.

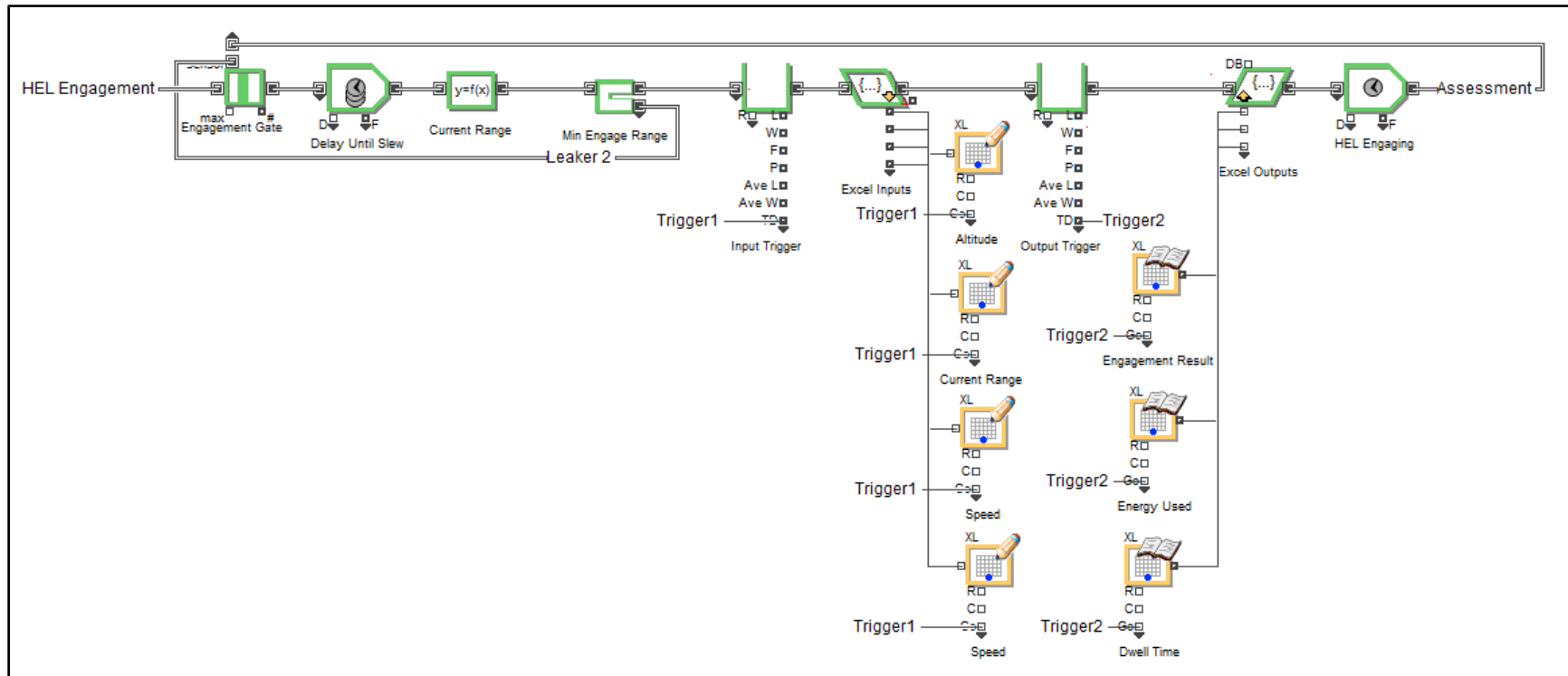


Figure 18. Engagement section of ExtendSim model

Using the four attributes and the data from ANCHOR, the Excel workbook calculates an engagement result, energy deposited at the target, and the dwell time. While the calculation occurs, the target proceeds to a second queue. This queue activates a trigger, telling the model to read the values calculated by the Excel workbook and then assigns those values as new attributes to the target. The model requires two triggers because of the speed of the simulation. Without the triggers, the target in the simulation would move from the write portion to the read portion faster than Excel could calculate the results. This would result in the target reading the results from the previous target in the engagement area. The triggers provide the model instructions on when to write the data and when to read the data.

The target then proceeds to the final block in the engagement area, which uses the dwell time calculated from Excel and delays the target's progression through the model by the appropriate amount of time. Afterwards, the target heads to the assessment area. Figure 19 shows the target moving to the assessment area of the model, which calculates the total energy used by the HEL system. The model then reads the energy used by the HEL and deposits it and the dwell time into a storage bin. At this point, the model reads the targets kill assessment from the Excel workbook. If assessment shows that the HEL failed to kill the target, the target proceeds through the bottom path and feeds back into the queue for another engagement attempt. The entire process repeats in the model until the target is killed or arrives within the minimum engagement range.

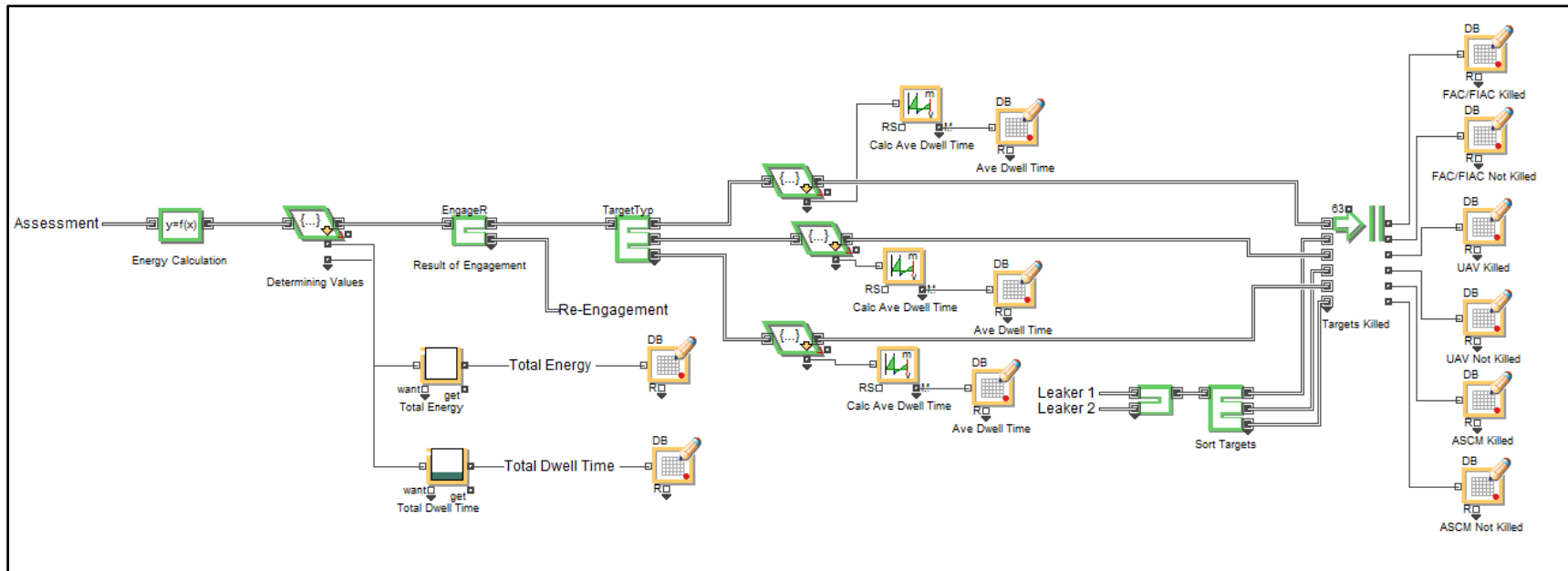


Figure 19. Energy calculation and system exit of ExtendSim model

The final step of the model is where all the targets exit the model. The targets that fail to have a minimum engagement time of 3 seconds exit through the branch called “Leaker 1,” the targets that end up inside the minimum engagement range exit through the branch “Leaker 2,” and the targets killed exit through the main branch of the model. The model writes the outputs to a database for collection and analysis. The models conduct sequential runs to gather more data for analysis. An analysis of all the data gathered provide a recommendation for the size of the energy storage system that the HEL requires.

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IV. ANALYSIS

The amount of energy storage a laser weapon needed to defeat a swarm of 30 FAC/FIAC and 20 UAVs before recharging was found to be approximately 200 MJ. This corresponds to the largest amount of energy used by the HEL out of all the different test cases. This chapter describes the analysis of the results from the data collected during each of the simulations. It also discusses the effects of visibility and the air/sea temperature difference on energy storage requirements. This chapter also discusses the different types of energy storage based on the size and weight needed to support the energy storage requirements.

While this study provides recommendations, the model results were constrained by the variables used in the models. This model used very strict constraints and assumptions for the engagement range, material composition of the targets, the location, etc. Further analysis is recommended using more accurate values for model parameters as this information becomes available. A major benefit of the model is that it can be easily adapted and modified for future research and analysis using a variety of situations and improved accuracy.

A. AMOUNT OF ENERGY STORAGE

Based on the simulations, the largest energy storage size required was found to occur for the FAC/FIAC threat, with bad visibility and with air temperature lower than sea temperature. The largest size of an energy storage system for a dual threat of FAC/FIAC and UAVs was similar and within a single standard deviation of this result. This showed that if designing a HEL to engage only FAC/FIAC, then the energy storage needed would be the same size to engage a combination of FAC/FIAC and UAVs. The amount of energy needed would be the same because the FAC/FIAC were lower priority targets in the dual engagement scenario due to their lower TTI. Since the model engaged FAC/FIAC after UAVs, the FAC/FIAC were at a closer range when engaged by the HEL. This meant that the dwell time and energy required from the HEL to destroy the FAC/FIAC decreased.

This one result showed the importance of defining a proper engagement range. Decreasing the overall engagement range of the HEL to 4 km may have reduced the amount of energy needed by the HEL. Table 13 shows the total amount of energy required averaged over 500 runs for each simulation. Figure 20 shows the amount of energy per FAC/FIAC in both a FAC/FIAC-only and a FAC/FIAC-UAV threat environment. The graph shows that the energy required per FAC/FIAC was consistently greater when the FAC/FIAC were the only threats.

Table 13 Results from simulations

Simulation Number	Total Energy Required by HEL, Averaged (MJ)	Standard Deviation (MJ)
1	156	10.1
2	146	8.42
3	151	9.08
4	166	10.7
5	160	9.78
6	162	9.20
7	209	17.6
8	209	18.4
9	210	16.3
10	52.3	2.03
11	51.9	2.00
12	52.2	2.00
13	57.3	2.58
14	56.9	2.42
15	56.9	2.38
16	77.2	4.17
17	77.7	4.54
18	77.4	4.20
19	13.0	3.34
20	13.1	3.37
21	No Data ^a	No Data
22	13.3	3.28
23	13.5	3.13
24	No Data	No Data
25	No Data	No Data
26	13.2	3.17
27	No Data	No Data
28	158	8.01
29	154	5.30
30	156	5.98
31	166	8.27
32	164	6.34
33	165	7.07
34	204	17.4
35	203	16.5
36	204	17.0

^aRuns 21, 24, 25, 27 were not completed; therefore no data was collected.
Explanation is outlined below.

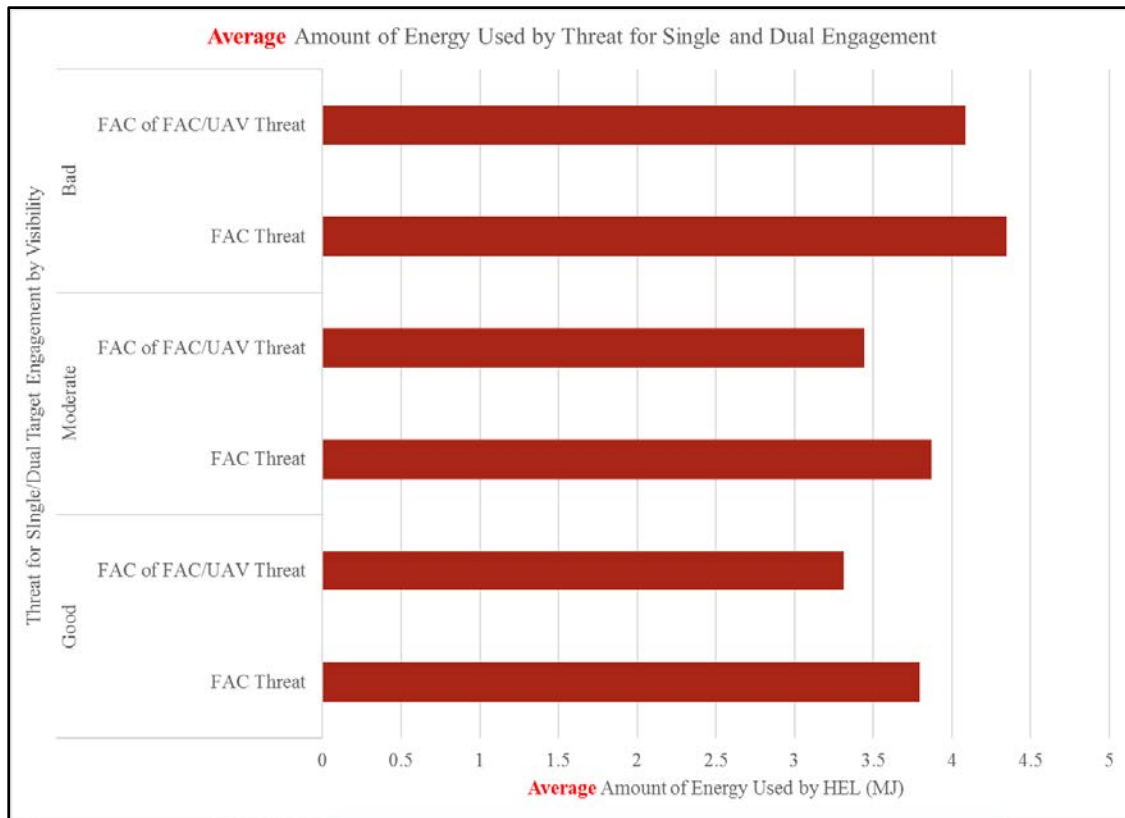


Figure 20. Average amount of energy used by threat type for single and dual engagement

Figure 20 is misleading in that when multiplying the energy per FAC/FIAC by 30 (the number of targets used in the simulation), the total energy storage is not equal to 200 MJ as previously stated. In the simulation, the model engages but does not kill some of the targets. The HEL still used the energy and recorded its use. The target would proceed back into the queue and be reengaged. Operationally, once the HEL starts an engagement on a target, the engagement does not end until destruction of the target. An improvement to the model would be creating a smaller loop so that once the HEL has decided to engage a target the target remains in the engagement loop until killed. Some targets return to the engagement queue because of the dwell time limit. Extending the maximum dwell time would have an effect on the amount of energy storage required.

If the HEL was used for the sole engagement of UAVs, the amount of energy storage needed to defeat 20 UAVs before recharging is approximately 80 MJ. Table 13

also shows these results. Per kill, the UAVs had a lower dwell time than the FAC/FIAC by approximately 1 second. Figure 21 shows this difference.

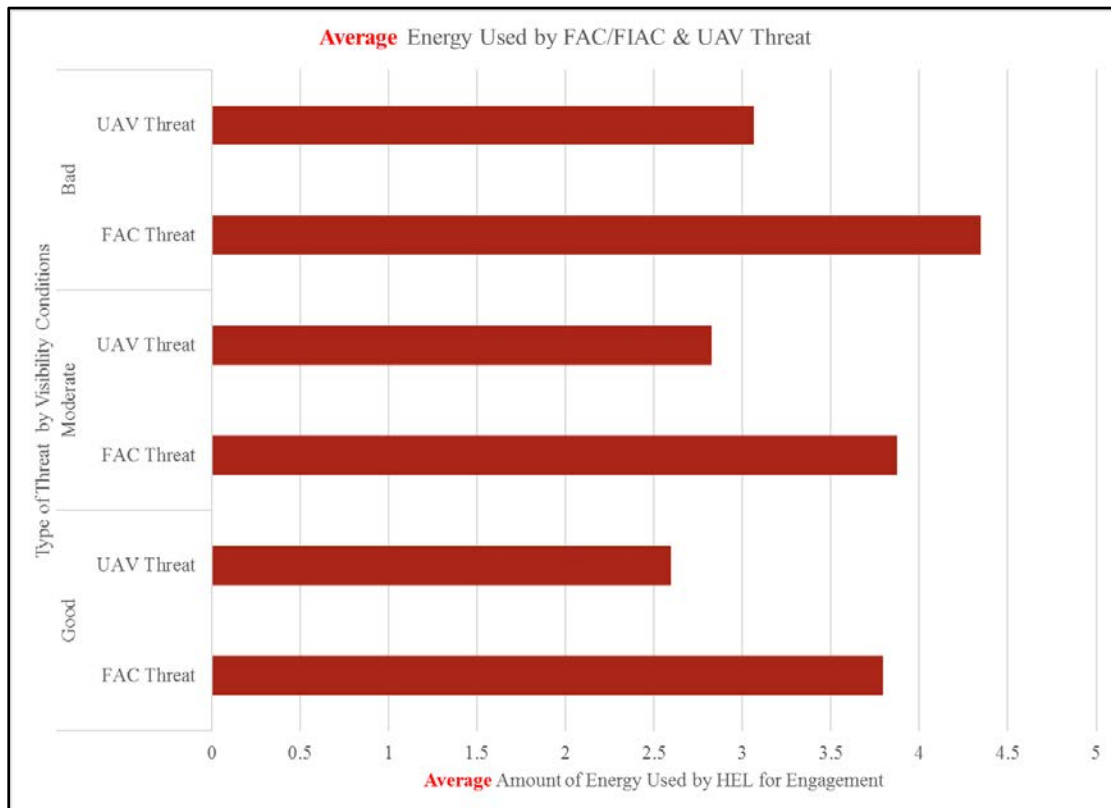


Figure 21. Average energy used by FAC/FIAC and UAV threats

This result shows the importance of two different variables. First, the UAV had a material thickness of 1 mm less than the FAC/FIAC. Second, the UAV engagement occurs at a higher altitude where there is less extinction and turbulence. Both of these factors combined to reduce the overall dwell time. While 1 second per target may seem insignificant, reducing the dwell time by 20-30 seconds for all targets reduces the amount of energy required by 12-18 MJ.

During the early stages of testing, a trend started to develop concerning the ASCM. The energy required by the HEL system for ASCM-only engagements remained at a consistent value. Further investigation showed that during the ASCM engagements the

model was only able to engage approximately 2 out of 5 ASCMs per scenario. This led to consistent energy requirements of 13 MJ regardless of any variables changed. Figure 22 shows the total energy required by the HEL and the total dwell time for 30 FAC/FIAC, 20 UAVs, and 5 ASCMs as the visibility decreases from good to bad. The air temperature is equal to the sea temperature so there is no increased turbulence. The numbers above each bar represents the average number of targets killed. In bad visibility, the number of FAC/FIAC or UAVs killed decreases by approximately 10% to 15%, while the amount of energy required increases by approximately 50%, compared to good visibility. Also, in bad visibility, no ASCMs were killed; in good visibility, only 1 out of 5 ASCMs were killed.

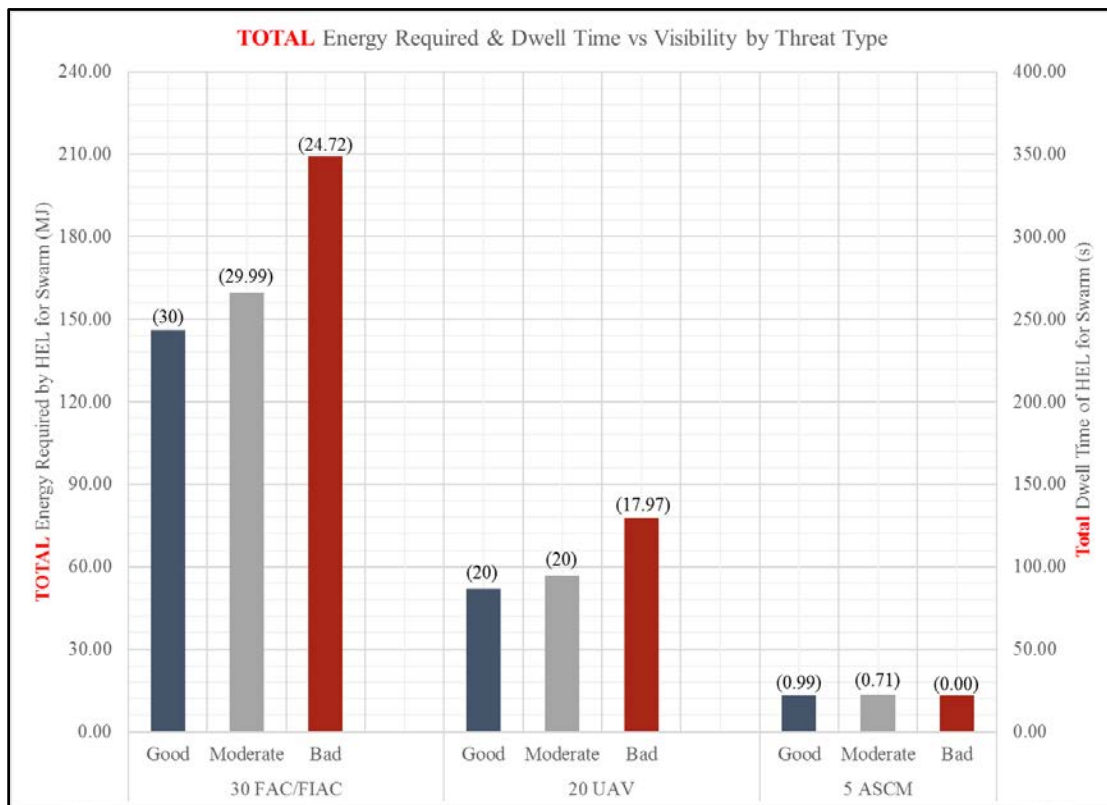


Figure 22. Total energy required for each threat by visibility

During simulations that used all three threats, the total energy required was within one standard deviation of the total energy required for simulations using a FAC/FIAC and UAV combination. Figure 23 shows a comparison of the total energy required and dwell time for all three threats and just FAC/FIAC and UAVs as visibility decreases. Adding the ASCMs did not have a significant impact on the results. Of the 5 ASCMs generated by the model, 1 to 2 were engaged (and rarely killed) and the rest reached the minimum engagement range before they could be engaged. This result was expected due to the design of ASCMs.

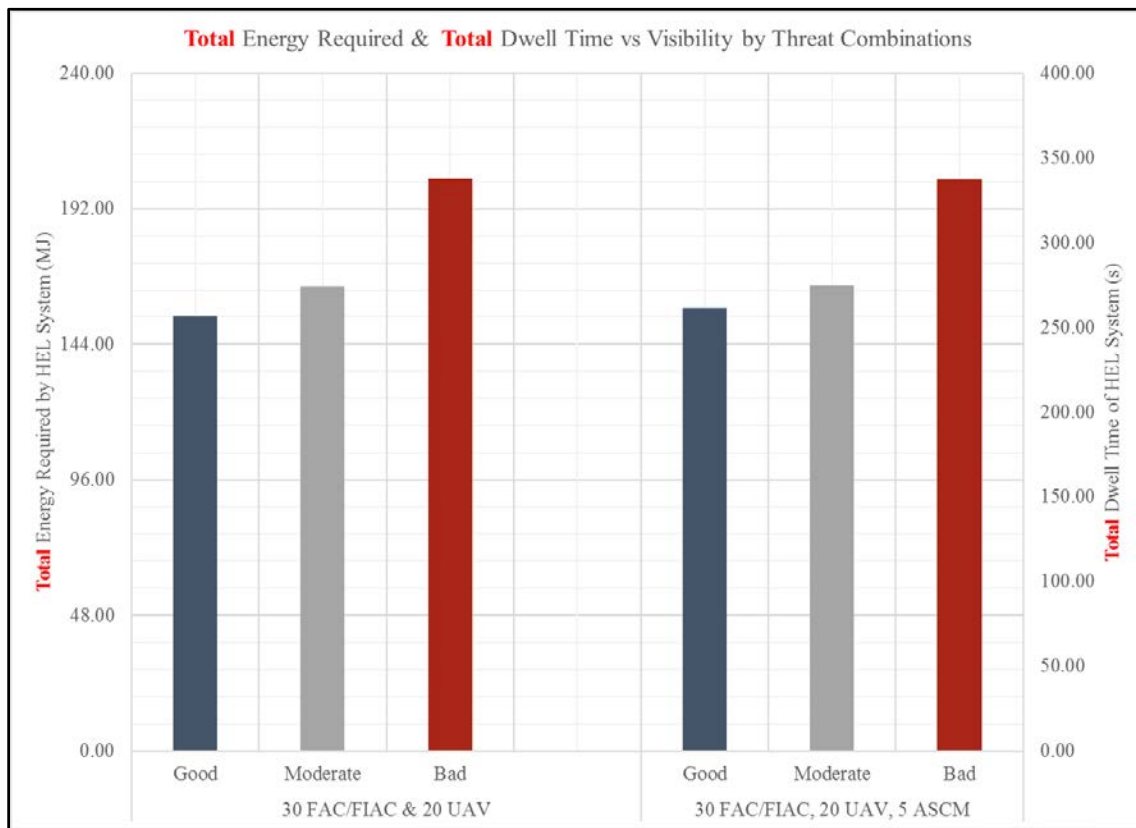


Figure 23. FAC/FIAC and UAV engagement compared to FAC/FIAC, UAV and ASCM engagement

The failure to kill the ASCMs is a direct result of the materials selected for the ASCM. The nose cone design of an ASCM uses materials that have higher melting points and low specific heat capacity. Most ASCMs deploy/launch from a cell style canister that generates a large amount of heat during the initial stages of launch and requires the missile to puncture through a protective seal. The stronger and thicker nose cones protect the missile during the initial stages of launch and for missiles exceeding the speed of sound, help disperse the heat that is generated from the friction of the missile against the air. Additionally, since the model “fires” all ASCMs nearly instantaneously, by the time the HEL finished engaging two of the ASCMs the other three have closed the distance to the ship and are within the minimum engagement range. If an enemy deploys ASCMs against a U.S. ship in this manner, the dwell time for the HEL is too great for annihilation of a swarm of ASCMs.

It was determined to remove ASCMs from testing. A 150 kW laser may still be able to achieve kills on an ASCM in other scenarios, such as a crossing shot. In a crossing scenario, the laser is targeting the body of the missile, which is made of thinner material, or targeting the fins of the missile, which help control its flight. In these cases a 150 kW laser may be sufficient although further research into the materials and weak points of an ASCM is required.

The recommendation of 200 MJ assumes that the targets attack so fast that the ship does not have any time to recharge the energy storage system. An attack that has a pause provides critical time for the ship to replenish energy stores and, depending on the type of energy storage and length of pause in the battle, this might allow for a smaller energy storage size. Additionally, if employing multiple laser systems, the amount of energy storage could be divided by the number of systems. For example, two HEL systems with 100 MJ of energy storage each, could handle a total of 30 FAC/FIAC and 20 UAVs. Increasing the number of systems onboard can reduce the size that the energy storage takes up and can help provide better coverage. However, since space on board is critical, it may not be practical to have more than two systems.

B. IMPACT OF ENVIRONMENTAL EFFECTS

During all the simulations, the energy required increased as the visibility decreased. This effect, while expected, occurs since a decrease in visibility means a larger concentration of aerosols in the atmosphere. The larger concentration of aerosols reduced the effectiveness through scattering and absorption. Figure 24 shows the general trend of the role visibility played in determining energy storage.

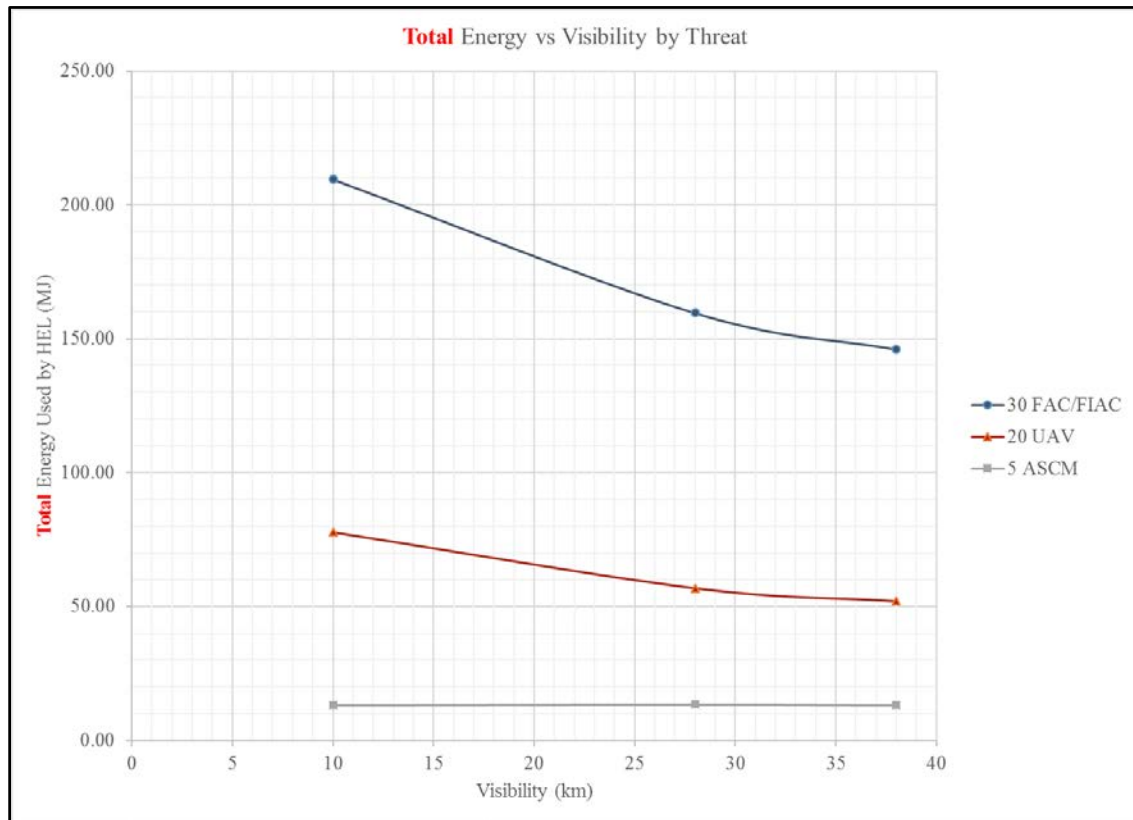


Figure 24. Energy used versus visibility for each threat type

The difference between the air and sea temperature provides interesting results. The air and sea temperature difference added more turbulence to the model. The engagements of FAC/FIAC all occurred in the high turbulence area near the ocean surface and suffered the effects more than the UAVs. Turbulence increased the amount of energy storage for the FAC/FIAC, but the increase was within two standard deviations from baseline. This

may be due in part to the very small temperature difference that occurs in the region. Figure 24 shows the total energy required versus visibility for the air to sea temperature difference for each of the FAC/FIAC simulations

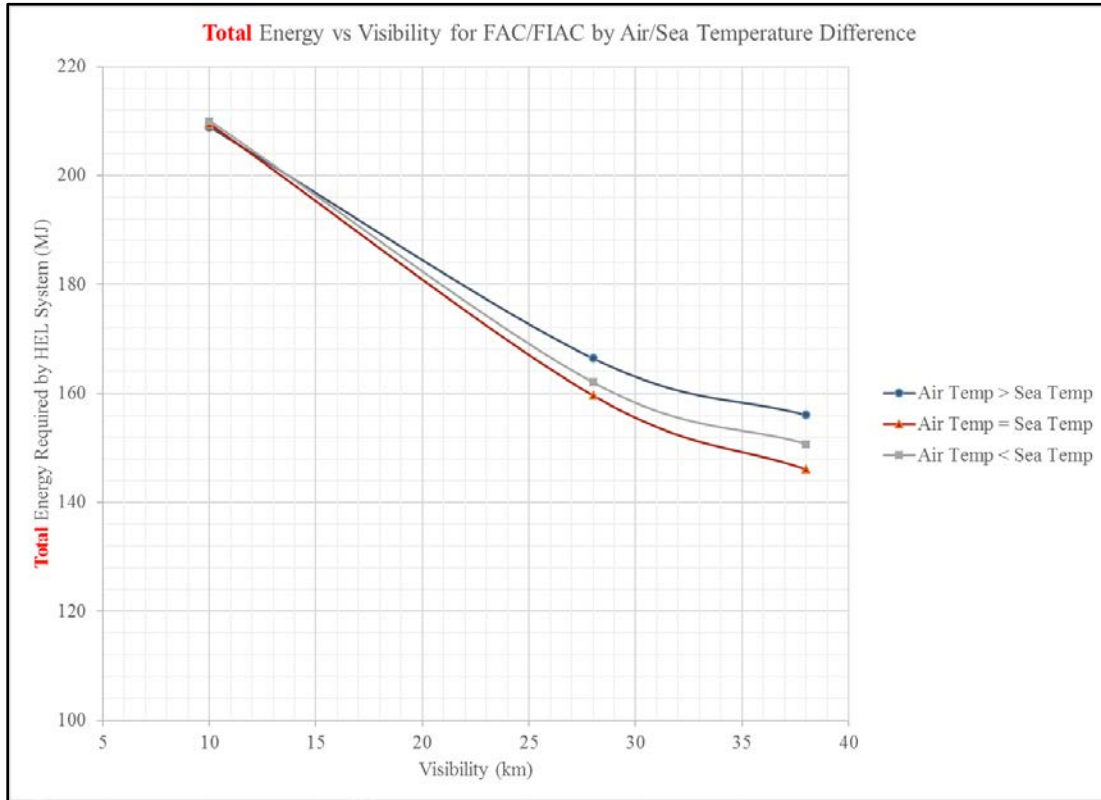


Figure 25. Energy required versus visibility for air/sea temperature difference of FAC/FIAC simulations

The figure shows that, at good visibility when the air temperature is higher than the sea temperature, the HEL required more energy to engage the FAC/FIAC. In poor visibility conditions, the total energy required is the same regardless of relationship between air and sea temperature. The main reason for this is that the turbulence and aerosol concentration are not competing effects, they are compounding. The laser beam can be scattered and absorbed by aerosols or scintillated by turbulence. The result is that more power is required to overcome these atmospheric effects.

Table 14 shows the average energy required for FAC/FIAC simulations at the different visibilities and relationship between the air and sea temperature. The model considered three cases: an air temperature 1.6 degrees higher than sea temperature, the air temperature equal to sea temperature and air temperature 0.8 degrees lower than sea temperature. The difference between when the air temperature is greater than sea temperature and the air temperature lower than sea temperature is the main reason for the different energies required for good and moderate visibility. In bad visibility, the average energy required was almost the same.

Table 14 Energy required (in MJ) for FAC/FIAC engagements at varying visibilities and air/sea temperature differences

	Air > Sea Temp (by 1.6 deg. F)	Air = Sea Temp (no difference)	Air < Sea Temp (by 0.8 deg. F)
Good Visibility	156	146	151
Moderate Visibility	166	160	162
Bad Visibility	209	209	210

This result is consistent with the measured effects of the air/sea temperature difference and amount of turbulence created. Figure 26 shows that when the air temperature is different from the sea temperature, the refractive index structure parameter (C_n^2) increases. The refractive index structure parameter is important in determining the effects of turbulence on beam quality (Frederickson 2016). A higher C_n^2 means that there is more scintillation and less irradiance on the target (Frederickson 2016).

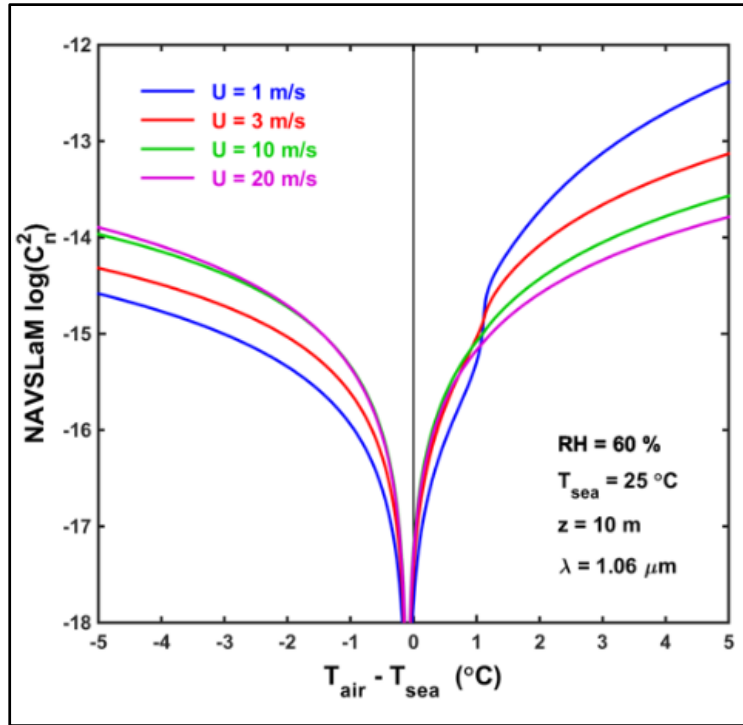


Figure 26. C_n^2 value relation to air/sea temperature difference. Source: Frederickson (2016).

Figure 26 shows that an air temperature 1.6 degrees Fahrenheit (0.9 degrees Celsius) greater than sea temperature has a higher C_n^2 than an air temperature 0.8 degrees Fahrenheit (0.4 degrees Celsius) lower than sea temperature. Since a greater C_n^2 means more turbulence, the HEL should require more energy, which it does.

C. ENERGY STORAGE CONSIDERATIONS

Given a need for 200 MJ of energy storage, this section discusses three types of energy storage methods and their respective sizes and weights, since those are important factors when placing a new system on board a U.S. Navy ship. Each of the systems also has several advantages and disadvantages that this section addresses. It is also important to note that the sizes and weights provided are only for the actual storage systems and do not include any support or other required systems. These systems need further analysis, as well as a cost-benefit analysis, to determine the best system by size, weight and cost.

1. Lead Acid Batteries

To achieve an energy storage system of 200 MJ with lead acid batteries would require 42 battery cells from the Furukawa Cycle Power series batteries (Furukawa Battery 2018). Using two 24-cell units would achieve this with a total weight of 4,060 kg and volume of 1.9 m³. Lead-acid batteries do require maintenance and have a limited life span. Furukawa states that the batteries have a 14-year life with 300 charge and discharge cycles per year. The life of the batteries depends on how much the ship uses the HEL in day-to-day operations. One of the bigger disadvantages of lead acid batteries is that discharging below 50% of its capacity affects the life of the battery and the rate at which the battery supplies energy to the system (Valiani 2016). The batteries also have a long recharge time, which means that recharging the batteries during a long engagement might not be possible (Furukawa Battery 2018). The biggest advantage to the lead-acid battery is that it is currently the only type of battery approved for large-scale shipboard use and widely used on submarines. This means that the supply chain process is already in place and it would be easy to acquire and use lead acid batteries for a HEL system.

2. Lithium-Iron Batteries

Once approved for shipboard use, lithium-iron batteries can reduce the amount of size and weight that an energy storage system would require. An energy storage system would require 48 Lithiumpros lithium-iron batteries. This would have a total weight of 660 kg and volume of 0.6 m³ (Lithium Pros n.d.). The weight is significantly less than that of the lead acid batteries and the volume less than half of lead acid batteries. Lithiumpros even advertises that the recharge time of a battery is 1 hour. While lead acid batteries have a discharge limit of 50%, the discharge limit of lithium batteries is 20% (Valiani 2016). These are all advantages over the lead acid batteries. However, they have not received approval for shipboard use, they have not had to withstand the rigors of a U.S. Navy vessel underway, and there is no support/supply chain to acquire new or replacement batteries.

3. Flywheels

Flywheel technology has made a resurgence and several companies are developing flywheels for shipboard use. From Jeremy Sylvester's thesis an 8.5 MW flywheel design, from the University of Texas, provides 27.8 MJ of energy storage, has a volume of 0.16 m³, and weighs 1,238 kg (Sylvester 2016). Assuming the flywheel size scales linearly, a flywheel with 200 MJ of energy will have a volume of 1.18 m³, and weigh 9,161 kg. However, as Jeremy states in his conclusions, the 8.5 MW flywheel provides enough energy because it will be able to recharge significantly faster. The recharge time can be a matter of seconds instead of hours. Flywheels also have longer life cycles and do not require constant replacement of batteries. Depending on the auxiliary systems, there might even be reduced maintenance. The short recharge times and high energy and power density make this a desirable energy storage system for HEL weapons.

V. CONCLUSION

The purpose of this research was to determine the amount of energy storage needed to engage and destroy swarm attacks of three different types of threats, examine the effects of environmental conditions on laser performance, and evaluate different types of energy storage systems. This research determined that a 200 MJ energy storage system would destroy a swarm of 30 FAC/FIAC and 20 UAVs, visibility and turbulence affect the amount of energy storage, and flywheels provide good potential as energy storage but need further development. This conclusion is based on the general assumptions and constraints for the model, and the assumptions for the friendly, enemy, and environmental variables. Any deviations from the attributes and/or assumptions require further research and analysis to determine the impact on the results. Modeling the energy storage system is an effective tool as the U.S. Navy seeks to integrate laser weapons on to their ships. However, the process of integration requires many tools of which models are just one. Consistently revising and validating the models improves their usefulness.

There are six major categories that the follow on research falls into: employment of the HEL weapon system, weather effects, target parameters, cooling requirements, types of energy storage, and laser parameters. Each of these categories improve the recommendations by refining and specifying variables and improving the general assumptions. Each can increase or decrease the amount of energy storage needed by the HEL. This list is not all-inclusive but gives a general outline of important research topics for further study.

Topics in the category of employment of the HEL weapon system include:

- The most effective engagement range per target.
- When to transition targets to other ship systems
- The most effective way to prioritize targets.
- The effect of operator delays (kill assessment, engagement order, etc.)

Topics in the category of weather effects include:

- Amount of energy storage required in other locations and seasons
- Humidity effects on laser performance
- The effect of rain on laser performance

Topics in the category of target parameters include:

- Classification of materials used on FAC/FIAC, UAVs and ASCMs
- Identifying vulnerability areas on targets
- Determining amount of energy for a hard kill on specific targets

Topics in the category of cooling requirements include:

- Cooling requirements of HEL system
- Cooling requirements of energy storage system

Topics in the category of type of energy storage include:

- SWAP-C requirements of auxiliary systems that support energy storage
- Analysis of recharge rates for energy storage systems

Topics in the category of laser parameters include:

- The effects of modifying laser parameters on energy storage
- Using adaptive optics and its impact on energy storage

This research laid the foundation for a concentrated effort of determining SWAP-C requirements for the energy storage system of a HEL. It created and developed an adaptable model that determines energy storage requirements, examined environmental effects on lasers and considered several different methods of energy storage. Defining the

size of the energy storage system is essential for determining the use of laser weapons on U.S. Navy ships.

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